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LOW-ANGLE FAULTING

R. T. CHAMBERLIN AND W. Z. MILLER
University of Chicago

CONTENTS

INTRODUCTION

In the literature of structural geology it is commonly stated that rigid materials subjected to non-rotational strain tend to fracture along planes which are inclined approximately 45° to the direction of applied force. This conclusion has been developed partly from a mathematical analysis of stress and strain relations and partly from results observed in the familiar practice of crushing cubes of building stone to determine their strength. That 45° is the angle at which rigid materials normally fracture under direct compressive stress appears to be very generally accepted. This angle, therefore, has come to be regarded by structural geologists as the theoretical angle at which thrust faulting, under ordinary conditions, should occur.

But if the actual angles of dip of a large number of thrust-fault planes in the earth be tabulated and averaged, it is found that the mean inclination is less than 45° from the horizontal. According to Leith an average compiled from folios of the United States Geological Survey gives a dip of 36° for planes of thrust faults and 78° for planes of normal faults.[1] An inspection of numerous cross-sections from various other countries gives results in fair agreement with these figures. The average dip angle of thrust-fault planes, as they occur in nature, is considerably less than 45°.

While the most prevalent type of thrust-fault plane, that of the ordinary reverse fault, dips somewhat less steeply than 45°, it still does not depart widely from that governing angle. Nevertheless, in notable variation from this, field studies in the last few years have brought to the attention of geologists impressive evidence of the prevalence and the great importance of what may well be called a different genus of fault, namely, the great low-angle overthrust. Its generic characteristics are the very low inclination of its fault plane and the extraordinary horizontal displacement often attained. Such low-angle overthrust faulting has been well described, as it is strikingly shown in the Northwest Highlands of Scotland, where the Moine, Ben More, Glencoul, and other remarkable thrusts form

[1] C. K. Leith, *Structural Geology*, 1913, p. 55.

classic examples of the genus (Fig. 1).[1] In the extreme north of Sutherland the various rock groups overlying the Moine thrust plane can be shown to have been driven westward for a distance of ten miles.[2] Horizontal shiftings of comparable magnitude occurred along the Ben More, Glencoul, and other planes of thrusting which lie beneath the Moine thrust and add to the remarkable nature of the phenomena. Though since thrown into gentle folds, in many places it is clear that these planes of slippage were originally not far from the horizontal. In some other portions of the British Isles analogous phenomena have been observed.

Similarly, in Scandinavia the very intense Caledonian deformation manifested itself in horizontal overthrusting of astonishing magnitude. The vertical displacement is slight, but the horizontal slip is measured in tens of kilometers.[3]

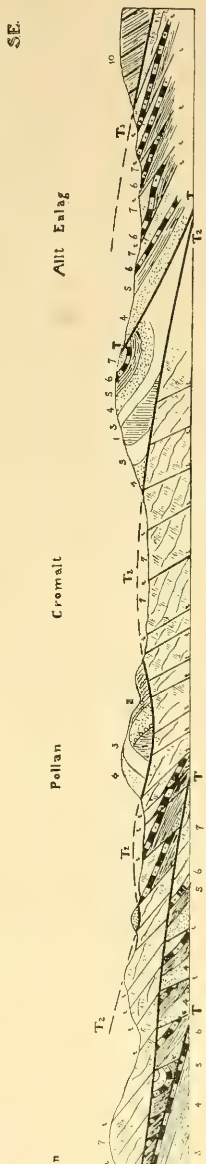

FIG. 1.—The Scottish Highland type of overthrust. Section from Elphin to Allt Ealag (about 6 miles in length). The thrust plane (T_3) near Allt Ealag on the right is the Moine overthrust. The gently folded thrust plane (T_2) which runs nearly the whole length of the section is that of the Ben More thrust. Two other major thrusts cut through the faulted slices near the left end of the section. Note the relation of the overthrusts, or major faults, to the minor reverse faults. From "Report on the Recent Work of the Geological Survey in the North-West Highlands of Scotland, Based on the Field-Notes and Maps of Messrs. B. N. Peach, J. Horne, W. Gunn, C. T. Clough, L. Hinxman and H. M. Cadell," *Quart. Jour. Geol. Soc.*, XLIV (1888), 426, Fig. 19.

[1] B. N. Peach, John Horne, W. Gunn, C. T. Clough, and L. W. Hinxman, "The Geological Structure of the Northwest Highlands of Scotland," *Mem. Geol. Surv. of Great Britain*, 1907, pp. 463–594.

[2] John Horne, *ibid.*, p. 469.

[3] A. E. Törnebohm, "Grunddragen af det Centrala Skandinaviens Bergbyggnad. Kongl," *Svenska Vet. Akad. Handl.*, Bd. 28, No. 5 (1896), pp. 190–95 and Pl. IV; P. J. Holmquist, "Bidrag till diskussionen om den skandinaviska fjällkedjans tektonik," *Geol. Fören. Förhandl*, XXIII (1901), 55–71.

In the southern Appalachian Mountains the Rome and Cartersville overthrusts run parallel to each other for over 200 miles. They are thought by Hayes to show horizontal displacements of not less than 4 miles and 11 miles respectively, and possibly much more. The inclination of the fault planes is here frequently as low as 5°; it is rarely more than 25°.[1] The steeper portions of the plane as now seen are largely the result of subsequent warping. Farther north, in Tennessee, a possible continuation of the Cartersville thrust is the Buffalo Mountain fault which, according to Keith, was a low-angle overthrust whose original displacement along the shear plane was at least 20 miles.[2] Subsequent folding and faulting have so disturbed this fault plane that its original inclination cannot be very closely determined.

More to the north, the earlier Taconic revolution also developed low-angle overthrusts. Of these may be noted the Great Western fault of eastern New York,[3] the St. Lawrence and Champlain fault, which runs from Vermont to the city of Quebec and beyond,[4] and possibly the Cowansville overthrust of Missisquoi and Brome counties, Quebec, though the age of the last has not been closely determined as yet. In any case the measured horizontal displacement of the last is 11 miles, and it is thought likely that the actual displacement was much greater.[5] It is a nearly horizontal overthrust, whose plane is very close to the present surface, and along which the Georgian slates on the east have been shoved over the Trenton slates and limestones of the Farnham series to the west.

The Rocky Mountains of Montana and Alberta are bordered on their eastern front, throughout at least 350 miles of their extent,

[1] C. W. Hayes, "The Overthrust Faults of the Southern Appalachians," *Bull. Geol. Soc. Amer.*, II (1891), 141–54.

[2] Arthur Keith, *U.S. Geol. Surv. Geol. Atlas, Roan Mountain* (*Tenn.*), Folio 151, 1907, p. 9.

[3] James D. Dana, *Manual of Geology* (4th ed.), 1895, p. 528; S. W. Ford, "Observations upon the Great Fault in the Vicinity of Schodack Landing, Rensellaer County, N.Y.," *Am. Jour. Sci.*, XXIX (1885), 16–19.

[4] G. A. Young, "The Geology and Petrography of Mount Yamaska, Province of Quebec," *Geol. Surv. Can. Ann. Rept.*, XVI (1906), 9.

[5] Robert Harvie, "Brome and Missisquoi Counties, Quebec," *Sum. Rept., Geol. Surv. Can.*, 1914, pp. 98–99.

by great overthrusts whose planes dip in under the mountains at low angles. McConnell has estimated that on the South Fork of the Short River in Alberta the horizontal displacement of the Cambrian strata—which here rest upon the Cretaceous—has been about 7 miles, while the vertical displacement amounts approximately to 15,000 feet.[1]

In the Glacier National Park of Montana, Willis found the Proterozoic strata which make up the outermost range (here called the Lewis Range) overthrust at least 7 miles upon the Cretaceous of the foothills. The dip of the thrust plane, as determined by Willis by graphic construction, ranges from $3°$ to $7° 45'$.[2] More recently Campbell has been able to show that where the Great Northern Railroad crosses the range this great mass of strata has been shoved at least 15 miles northeastward along the Lewis thrust plane, and were the original position of the mountain mass known the distance might prove to be much greater.[3]

At the International Boundary the northward continuation of the Lewis thrust has been termed the Waterton Lake thrust by Daly. The known extent of the bodily movement here represented is about 8 miles, as measured on the perpendicular to the line tangent to Chief Mountain and the outermost mountains of the Clarke Range. But the actual movement, according to Daly, has probably been 10 miles or more, and may be as much as 40 miles, for "it is not impossible that the entire Clarke Range (the equivalent of the Livingston Range of Willis) in this region represents a gigantic block loosened from its ancient foundations, like the Mount Wilson or Chief Mountain massifs, and bodily forced over the Cretaceous or Carboniferous formations."[4]

The Willard thrust discovered by Blackwelder in the Wasatch Mountains of Utah has a displacement, so far as exposed, of about 4 miles, though this is probably but a small fraction of its total

[1] R. G. McConnell, *Geol. Surv. Can.*, II (1886), Part D, p. 33.

[2] Bailey Willis, "Stratigraphy and Structure, Lewis and Livingston Ranges, Montana," *Bull. Geol. Soc. Amer.*, XIII (1902), 331–43.

[3] M. R. Campbell, "The Glacier National Park," *Bull. 600, U.S. Geol. Surv.*, 1914, p. 12.

[4] R. A. Daly, "Geology of the North American Cordillera at the Forty-Ninth Parallel," *Mem. 38, Geol. Surv. Can.*, Part I (1912), p. 91.

displacement. Though the fault plane locally has a dip as high as 50° owing to later warping, it averages about 15°.[1]

The Bannock overthrust, recently described by Richards and Mansfield, when traced through southeastern Idaho and Utah along its course, now made sinuous by erosion, has a length of approximately 270 miles, and involves a horizontal displacement of not less than 12 miles.[2] The thrust plane itself is a gently undulating surface nowhere steeply inclined, sometimes dipping to the east and sometimes to the west. If this slight plication be the result of subsequent folding, the shear plane must originally have been very nearly horizontal.

In eastern Wyoming the Absaroka and Darby faults are really of the overthrust variety, although what remains of these planes shows a higher angle of inclination than most of the preceding.[3] The fault plane of the Darby thrust is, in general, not far from parallel to the bedding of the overthrust sheet. East of Yellowstone National Park the Hart Mountain overthrust is thought by Dake to show a displacement of not less than 22 miles, making no allowance for recession of the eastern front by erosion.[4] Assuming average thickness for the beds involved, the vertical displacement is over 6,000 feet.

In the Alps, so long and carefully studied, some of the most remarkable structures known to geologists are still in process of being worked out. As yet there is lack of perfect accord as to some of the features of their interpretation. They have commonly been interpreted as extraordinary and wonderfully drawn-out overfolds (*nappes de recouvrement*). Among certain geologists there has developed a disposition to substitute, in interpretation, overthrust sheets of the Scottish Highland type[5] for these extreme

[1] Eliot Blackwelder, "New Light on the Geology of the Wasatch Mountains, Utah," *Bull. Geol. Soc. Amer.*, XXI (1910), 517–42.

[2] R. W. Richards and G. R. Mansfield, "The Bannock Overthrust, a Major Fault in Southeastern Idaho and Northeastern Utah," *Jour. Geol.*, XX (1912), 681–709.

[3] Alfred R. Schultz, "Geology and Geography of a Portion of Lincoln County, Wyoming," *Bull. 543, U.S. Geol. Surv.*, 1914, pp. 84–87, and structure sections.

[4] C. L. Dake, "The Hart Mountain Overthrust and Associated Structures in Park County, Wyoming," *Jour. Geol.*, XXVI, No. 1 (1918), p. 50.

[5] Bailey Willis, "Report on an Investigation of the Geological Structure of the Alps," *Smithsonian Misc. Coll.*, LVI (1912), No. 31, pp. 1–13; also James Geikie, *Mountains, Their Origin, Growth, and Decay*, 1913, pp. 116–17.

overfolds. If this be the true explanation, it would add to our list this remarkable structure of the Alps as a most pronounced and complicated case of low-angle faulting.

Similar structures have been reported from Spain, Euboea, the Balkans, and the island of Timor; in the last case an extensive sheet of shallow water strata, ranging in age from Triassic to Eocene, has been thrust over what appear to be deep-sea deposits of nearly the same age.[1]

Detailed studies elsewhere—practically the world over, indeed—are bringing to light overthrust faults of great displacement along gently inclined planes. This sort of faulting seems, therefore, to constitute a phenomenon of a definite, independent type. It seems to belong to a genus of its own, distinct from the ordinary reverse fault, though the two are no doubt connected by composite types that bind them together. The common reverse fault is defined by displacement along planes neighboring 45° or a little less, and is confined to more limited movement on these planes, while the great overthrusts slide along planes that approach horizontality and involve displacements of astonishing magnitude. Though each great low-angle overthrust is commonly attended by a retinue of reverse faults of lesser magnitude—a fact which suggests that there may be a kinship between them—nevertheless an inspection of any good section, as in the Scottish Highlands, shows a radical difference between the two types. Some distinctive feature seems to be added to simple straight compression to form the low-angle overthrusts.

PREVIOUS INVESTIGATIONS

Willis has divided thrust faults into four classes, the break-thrust, stretch-thrust, shear-thrust, and erosion-thrust. Of these the shear-thrust and the erosion-thrust are low-angled overthrusts, while the other two classes belong to the more common group of reverse faults. The shear-thrust is a class to cover the conspicuous Scottish Highland type, while the erosion-thrust covers a special case of alternate competent and incompetent strata in which the upper competent formation carrying the thrust is first removed

[1] G. A. F. Molengraaff, "Folded Mountain Chains, Overthrust Sheets, and Block Faulted Mountains in the East Indian Archipelago," *Compte Rendu, Congrès Géol. Int.* (Toronto, 1913), pp. 689–702.

from the crest of a broad anticline by erosion. When subjected to further lateral thrust, the upper beds on one limb of this anticline, encountering little resistance in front, ride forward over the subaërial surface.[1] Related to this form of erosion-thrust is another special type described by Hayes from the southern Appalachians.

Thus the field of the low-angle fault is not an unexplored one, since explanations have been offered for certain special types of overthrusts. The very definite explanation for the Rome and Cartersville overthrusts of the Southern Appalachians was worked out by Hayes as early as 1891.[2] The key of this explanation was suggested by the massive and peculiarly competent dolomite formations which alternate with weaker shale layers. In this

FIG. 2.—A theoretical section to represent the position of the fault plane (PP') in the Rome and Cartersville thrusts. From Hayes.

type of deformation the strata are thought to have first flexed into a pair of gentle anticlinal bends some notable distance apart. Between the flexures the strata remained essentially undisturbed. Finally a break occurred near the crest of one of the anticlines, and the thick, competent formations sheared more or less horizontally along a slippage plane which followed closely the bedding of the weak shales (Fig. 2).

The erosion-thrusts of Willis and the special form so clearly described by Hayes are dependent upon appropriate rock strata and structure, and thus these explanations, while they fit admirably the conditions in the southern Appalachians for which they were devised, do not apply to various other overthrusts where the necessary stratigraphic conditions do not obtain. They thus constitute a particular type due to special conditions. They do not apply to the very remarkable overthrusts of the Scottish High-

[1] Bailey Willis, "Mechanics of Appalachian Structure," *U.S. Geol. Surv., 13th Ann. Rept.*, Part II (1893), pp. 222–23.

[2] C. W. Hayes, *loc. cit.*, II (1891), 141–54.

lands, where the thrust planes cut through very heterogeneous assemblages of rock material. Different principles apparently control the latter.

It was with a view to obtaining light upon the mechanism of the Scotch overthrusts that Cadell, in 1888, even earlier than Hayes, undertook his experimental researches which since have become classic. In these instructive researches Cadell made use of a pressure box, one side of which could be thrust forward by means of a powerful screw. In this box he built up a succession of layers of plaster of Paris, interstratified with layers of sand, to imitate beds in the earth. After the plaster had set into rigid strata, lateral pressure was applied by means of the screw which moved the pressure block. In this manner, as the final outcome of many trials, he succeeded in imitating rather closely the peculiar imbricate and overthrust structure which the members of the Scottish survey were deciphering from the greatly disturbed terranes of the Northwest Highlands.[1]

Those of Cadell's conclusions which relate to overthrusting may be quoted:

1. Horizontal pressure applied at one point is not propagated far forward into a mass of strata.

2. The compressed mass tends to find relief along a series of gently inclined thrust planes, which dip toward the side from which pressure is exerted.

3. After a certain amount of heaping up along a series of minor thrust planes, the heaped-up mass tends to rise and ride forward bodily along major thrust planes.

4. Thrust planes and reversed faults are not necessarily developed from split overfolds, but often originate at once on application of horizontal pressure.

5. A thrust plane below may pass into an anticline above, and never reach the surface.

6. A major thrust plane above may, and probably always does, originate in a fold below.

7. A thrust plane may branch into smaller thrust planes, or pass into an overfold along the strike.

8. The front portion of a mass of rock being pushed along a thrust plane tends to bow forward and roll under the back portion.

9. The more rigid the rock the better will the phenomena of thrusting be exhibited.

[1] H. M. Cadell, "Experimental Researches in Mountain Building," *Trans. Roy. Soc. Edinburgh*, XXXV (1890), 337–57.

The result of Cadell's experimentation was to produce a concrete picture of the manner in which the complex structure of the Northwest Highlands may have developed. As pressure was gradually applied, the artificially prepared strata were first sliced into separate blocks by ordinary reverse slice faults which dipped in the direction from which the pressure was applied. A piling up of the sliced blocks followed. After sufficient piling up had occurred, a low-angle major thrust plane broke through the piled-up mass of slices, and the whole overlying mass rode forward bodily upon this gently inclined plane which Cadell termed the "sole" (Fig. 3). This behavior would seem to suggest that the heaping up of material

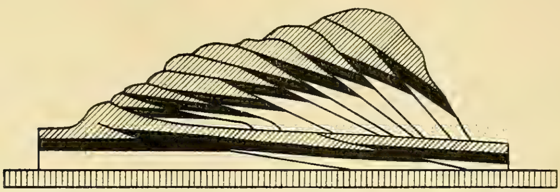

FIG. 3.—Major thrust plane, or "sole," cutting across minor slice faults. After Cadell.

is an important factor in determining the subsequent break along the low-angled "sole."

A pressure box patterned somewhat after that of Cadell was employed by Willis in his experiments upon Appalachian structure.[1] But in these interesting and well-known experimental researches folding rather than faulting was the prime object of the investigation. To obtain the desired results Willis used somewhat softer materials than those employed by Cadell, and heavily weighted the strata with a thick covering of shot to prevent too ready yielding. The hardest layers, in most cases, were composed of equal parts of plaster and wax, while the less competent beds were still further softened by the addition of turpentine, and often by leaving out plaster altogether. Fracturing occurred only very incidentally.

Further researches by Paulcke were directed toward reproducing experimentally the folds of the Jura, and the marvelous overfolded

[1] Bailey Willis, *U. S. Geol. Surv., 13th Ann. Rept.*, Part II (1893), Pl. LXVI, opposite p. 258.

and overthrust structure of the Alps.[1] With this end in view Paulcke adopted a stratigraphic series which, in most cases, comprised a thick basal layer of sand, above which were eight or nine alternating layers of clay and plaster. The mass was then weighted above by a very thick covering of sand. Because of the nature of the materials, fracturing of quite variable sorts developed—both typical reverse faults and a few low-angle overthrusts in which a strong plaster bed carrying the thrust was shoved bodily over the less competent clayey material beneath. But the brittle layers of plaster broke into numerous small rectangular blocks in addition to the major folding and faulting, and these small blocks were so rotated, shattered, and irregularly displaced as to mask much of the more significant behavior of the strata under compression. In general outlines, however, various cross-sections of the Alps were reproduced.

The experiments of Cadell suggested that the piling up of weight may be an important factor in determining the low-angle overthrusts, and that perhaps the question may be solved by experimentation. This stimulated us to attempt further experimentation in an effort to determine the influence of various contributing factors upon the angle of faulting.

METHODS OF PRESENT EXPERIMENTAL INVESTIGATION

Apparatus.—For these studies a pressure box was constructed along lines similar to those adopted by Cadell and Willis (see Fig. 4). This box differed, however, from the previous ones in having screws and movable pressure blocks at both ends, instead of solely at one end. Pressures could thus be applied from opposite directions whenever desired. But it was found, early in the progress of the work, that these pressure blocks frequently manifested a strong tendency to rise up from the floor of the box and to become tilted as the faulting of the strata progressed. To prevent this, long steel guide flanges were bolted on the inner sides of the box at a height of about an eighth of an inch above the top of the pressure block. With this control the pressure block could only move forward and backward, and the tilting of the block was thus practically

[1] W. Paulcke, *Das Experiment in der Geologie* (Berlin, 1912), pp. 74–108.

eliminated. One side of the box was constructed so that it could be removed as often as desired during the course of each experiment in order to note the nature and progress of the deformation and to photograph the structure developed. Pressures were applied by means of a $1\frac{1}{4}$-inch steel screw turned by hand, operating upon a lever arm of 24 inches. At the opposite end of the box the other pressure block was moved by a 1-inch screw. This was much less frequently used. These screws were capable of developing such thrusts that one of the chief difficulties was to secure an apparatus of sufficient strength to withstand the stresses to which it was

FIG. 4.—Pressure box with a movable thrusting block at each end. The detachable side has been removed to permit a view of the interior.

subjected. Various strengthening devices were employed. If another apparatus were attempted, it would be constructed entirely of steel.

Materials.—Before attempting experiments upon a succession of strata of varying competency, as would be the case in nature, it was essential to determine the effect of compressive stresses on homogeneous material. Both rigid and plastic materials were compressed in the crushing machine to determine their different behavior under stress. For rigid material either plaster of Paris or a mixture of plaster with a small amount of clay was used. As a result of many trials it was found that to secure rigid, brittle material, such as best illustrates faulting, a mixture of three parts of plaster and one part of clay gave the best results. To develop greater plasticity the proportion of clay was steadily increased, and in various cases a certain proportion of sand was added until there was as much as two parts of clay and sand to one part of plaster.

In preparing this combination it seemed best to mix the plaster and clay dry and, when thoroughly mixed, to put the mixture in the machine in that state and wet it down with water as the material was poured in. The most homogeneous mixtures were developed in this manner.

When the box was filled to the desired depth, the wet mass was allowed to set for a period of from three to seven days, until the material was not readily dented with a trowel. The length of time required depended considerably upon the combination of materials used. The greater the proportion of clay the longer the period of time necessary for the material to harden. When deemed sufficiently hard, the screw was turned and the process of crushing begun. The pressure was brought to bear gradually. After a single turn of the screw, or only a small fraction of a turn, the side of the box was removed and the resulting deformation observed. This cautious turning of the screw, with frequent halts to view the results, was maintained till the end of each experiment.

After treating structureless homogeneous materials of a considerable range of competency, tests were made with bedded homogeneous materials to discover how simple bedding planes, as lines of weakness, influenced the angle of faulting. The procedure was to place a layer of equal parts of plaster and clay in the machine, soak it thoroughly with water, and quickly smooth it with a trowel. After a few minutes, when the bed had hardened slightly, another layer of the same material was laid upon it and treated in the same manner. In this way five or six layers were built up. The whole mass was then allowed to set until rigid, and afterward crushed.

To test the influence of an alternation of beds of different competency upon the angle of faulting, Cadell's line of attack was followed at the outset. Plaster and sand were used respectively for the competent and incompetent beds. The sand was poured into the machine, bedded down, and then well dampened with water. While still wet a layer of pure plaster was added, followed as quickly as possible by another layer of sand and another of plaster, until four to six layers were built up. The plaster absorbed water at once and became hard, so that a long wait before crushing was less necessary than when clay was involved.

Troublesome difficulties arose from the use of these materials. Owing to the incoherence of the sand, the competent plaster layers, instead of rising along a single fault plane after fracturing had occurred, were thrust into the sand layers, producing a dovetail effect. Obviously it was necessary to add something to the sand to correct this and to give the sand more coherence, and yet at the same time the sand layers were to be kept relatively incompetent. With this end in view varying amounts of plaster were added to the sand and the result noted. But it was found that if sufficient plaster were added to furnish the desirable coherency, the layer became too competent for the purpose of the experiment. Clay alone was tried, but owing to the weakness of the clay, or its lack of adhesion to the plaster, dovetailing again resulted. To obviate this, plaster was added to the clay in the proportion of about two parts of clay, with some sand, to one part of plaster. This combination was successful, though in different experiments, where varying degrees of competency were desired, somewhat different proportions were used. As would be expected, the plaster layers carried the thrust, and the whole mass acted as a rigid body until these competent layers were fractured. The influence of softer layers after fracturing will be discussed later.

In certain experiments it was desired to give the competent layers somewhat greater plasticity. This necessitated increasing the plasticity of the incompetent layers as well, in order to keep the relative competency the same. For this series of experiments a mixture of plaster, clay, and sand was used for the competent beds, varying in proportion from three parts of plaster and one of clay and sand to two parts of plaster and one of combined clay and sand. For the incompetent beds either pure clay was used, or a mixture of clay and plaster varying in proportion from four of clay and one of plaster to two of clay and one of plaster. Such strata required from three to seven days to harden, depending upon the proportions of clay and plaster used.

RELATION OF FAULTS TO STRESS AND STRAIN

Stresses may be defined as the forces developed within different parts of a structure under the action of external forces operat-

ing upon it, and strain as the change in the shape or dimensions of the body resulting from stress. Strains may be dilatational, in which there is change of volume without change of form, or distortional, in which the form of the body is changed without changing the volume. Of these the latter is by far the more important in the deformation of rocks. Distortional strains may result from three kinds of stress—tensile, compressive, and shearing stress—torsion being regarded as shearing by twisting. Various combinations of these stresses are of frequent occurrence.

In the problem of thrust faulting under consideration, the deformation results from the action of compressive stresses and shearing stresses, with tension only a very subordinate and incidental factor. The operation of these stresses may be analyzed as follows:[1]

Consider a rectangular block with pressure P applied uniformly to a face to find the stress on the oblique section *mnop*.

Resolve P into normal (N) and tangential (T) components. If the angle between the direction of application of force (P) and the plane of the oblique section (*mnop*) be designated θ, then

$$N = P \sin \theta$$
$$T = P \cos \theta$$

The tangential component T tends to cause sliding along the section *mnop* and is called the shearing stress. The normal component N is called the normal or direct stress.

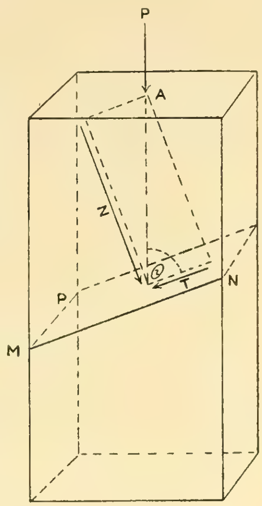

FIG. 5.—Diagram to represent the normal or direct stress (N) and the tangential or shearing stress (T) operating on an oblique section (*mnop*). The force (P) is applied uniformly on face A.

Let a represent the area of the cross-section of the block, or column, upon which the force is applied. Then the area of the oblique section *mnop* equals $a \csc \theta$.

[1] W. C. Unwin, *The Testing of Materials of Construction*, 1910, pp. 22–23; R. J. Woods, *The Theory of Structures*, London, 1909, pp. 1–4.

Hence the stress per unit area, or the intensity of stress, on section *mnop* is seen to be:

$$(1) \qquad \text{Normal stress } (Pn) = \frac{P \sin \theta}{a \csc \theta} = P \sin^2 \theta .$$

$$(2) \qquad \text{Tangential stress } (Pt) = \frac{P \cos \theta}{a \csc \theta} = P \sin \theta \cos \theta .$$

For an oblique section at right angles to *mnop* substitute $90^\circ - \theta$ for θ and get

$$P'n = P \cos^2 \theta .$$

$$P't = P \cos \theta \sin \theta = Pt .$$

Thus the intensity of tangential stress is the same on two oblique sections at right angles to each other.

The value of $P \sin \theta \cos \theta$ reaches a maximum for $\theta = 45^\circ$ when it equals $\frac{1}{2}P$. The intensity of the shearing stress is therefore greatest for planes at 45° to the line of propagation of the force.

Since the intensity of the shearing stress is as a maximum when $\theta = 45^\circ$, it was natural enough to suppose that fracturing under compressive stress should occur normally along planes inclined 45° to the line of application of the force, and in the familiar practice of crushing cubes of stone, cement, wood, etc., in testing machines to determine their strength for building purposes, experience is that the blocks break at angles approaching 45°, though most frequently the angle is somewhat less than this. Forty-five degrees is the angle which is commonly stated to be the angle of fracture in the geologic literature which deals with faulting and jointing under compressive stresses.

But, as has been noted, many thrust-fault planes are found to dip at angles much less than 45°, and short blocks in the crushing machine very commonly break at angles as low as 30°. Fracturing at 30° in our experiments has been commoner than at the higher angle of 45°. What is the meaning of this? Experimental error fails to satisfy the discrepancy, as an error of 15° is unlikely and the persistence of 30° and 35° breaks shows that there is some important factor, or factors, in operation which have not been considered. Let us therefore consider some of the possible factors which may operate to reduce the angle of fracture from the theoretical 45°.

FACTORS WHICH LOWER ANGLE OF FAULTING

A. EFFECT OF NORMAL COMPONENT OF STRESS

While the tangential or shearing stress ($Pt=P \sin\theta \cos\theta$) reaches its greatest intensity along planes inclined 45° to the line of application of the force P, it is also true, as has just been shown, that the intensity of the stress at right angles to this ($Pn=P \sin^2\theta$) is likewise great. This normal stress obviously acts as a frictional resistance to shearing by the tangential stress. The value of this frictional resistance depends on the shearing strength of the material when not in compression.[1] As to the potency of this factor, Church states that the presence of compressive stress normal to the 45° plane is sufficient to strengthen the material for shearing in that plane, causing separation to occur along a plane where the compressive stress is considerably less.[2]

Let us see how this plane will be inclined. The intensity of the normal stress is expressed by

$$Pn=P \sin^2\theta .$$

Its intensity increases as θ increases, and diminishes as θ decreases (see Fig. 6). Hence the lower the angle of the fracture plane, the less will be the frictional resistance due to normal compressive stress.

The intensity of tangential or shearing stress ($Pt=P \sin\theta \cos\theta$) is greatest when $\theta=45°$, and diminishes as θ becomes less. Shearing can occur only when this exceeds the shearing strength of the material. Here is a limiting factor.

Comparing

$$Pn=P \sin^2\theta$$

and

$$Pt=P \sin\theta \cos\theta ,$$

it is seen that as θ becomes less $P \sin^2\theta$ diminishes in value more rapidly than $P \sin\theta \cos\theta$ or, in other words, as the angle θ is lowered from 45°, the intensity of normal stress is reduced more rapidly than the intensity of the tangential stress. Therefore,

[1] W. C. Unwin, *op. cit.*, p. 419.

[2] I. P. Church, *Mechanics of Engineering* (New York, 1913), p. 220.

since the resistance due to the normal stress is reduced more rapidly than the intensity of tangential stress, as the angle is lowered from 45°, fracturing so far as determined solely by these two factors is made easier with the reduction of angle. But on the other hand, the intensity of tangential stress must exceed the shearing strength of the material in order to produce fracturing, and since this intensity diminishes with a lowering of the angle from 45° downward, the angle must not be too low to allow the

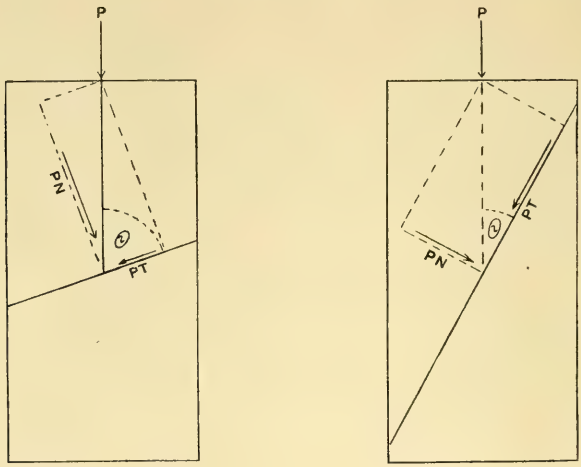

FIG. 6.—Diagrams to show how the relative intensity of the normal (*Pn*) and tangential (*Pt*) stresses on an oblique section is a function of the inclination of the section to the direction of application of the force. In the left-hand figure the direct stress exceeds the tangential in intensity; in the right-hand figure, with a lessening of the angle between the direction of the force and the plane of the section, the tangential stress is the more intense.

requisite intensity. This is the limiting factor which prevents breaking at too low an angle. The breaking plane is thus determined by a balance of these three factors. This helps to explain why homogeneous material, when subjected to compression, so persistently fractures at angles lower than 45°, although the shearing stresses reach their greatest intensity in the 45° planes.[1]

[1] A mathematical analysis leads to the conclusion that the inclination of the surface along which there is the greatest tendency to rupture is lowered from 45° by $\frac{\phi}{2}$, where ϕ is the angle of friction, or angle of repose, of the grains of the material. For

But as the favorite angles of fracturing for these blocks of homogeneous material appear to be 30°, or 35°, or 40°, the effect of frictional resistance due to the component of stress normal to the fracture plane clearly is not an adequate explanation of the great, low-angled overthrusts whose planes of fracture are commonly inclined at only 5° or 10° from the horizontal. There must be other factors.

B. EFFECT OF HETEROGENEITY OF MATERIAL

It is to be recognized that the angle of faulting is to some extent dependent upon the uniformity or heterogeneity of the material. Tests on the strength of materials seem to show that most blocks fail by a combination of shear and splitting. Only short blocks of very uniform texture will fail by shear entirely across the section in one plane.[1] Heterogeneous material which introduces differences in composition introduces irregularities in fracturing, and these irregularities are prevailingly in the nature of a lowering of the angle of fracture. But this alone will hardly explain the great overthrusts.

C. POSSIBLE INFLUENCE OF LENGTH AND SHAPE

Length.—The short column, whose length is not more than five times its diameter, fails by direct crushing. A longer column fails partly by crushing and partly by bending.[2] Thus a distinction is made in engineering practice between the behavior of the short block and the long column. The long column first bends and then splits obliquely. That the long column should be weaker than short blocks of the same material and cross-section is evident, but the theoretical treatment of its behavior is much less satisfactory than in other cases of flexure.[3] The breaking load for long columns, however, is represented by Euler's formula:

$$P=\frac{\pi^2 EI}{l^2}$$

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cast iron the usual value of θ is about 35°, corresponding to a value for ϕ of 20° (Arthur Morley, *Strength of Materials* [London, 1913], pp. 55–56). Hodgkinson's experiments with cast iron have shown that 35° is the common angle of rupture for this material (cited by Church, *Mechanics of Engineering*, p. 220).

[1] James E. Boyd, *The Strength of Materials*, 1911, p. 48.

[2] R. J. Woods, *op. cit.*, p. 205.

[3] I. P. Church, *Mechanics of Engineering*, 1913, p. 360.

where P is the limiting load which the column can support, E is Young's modulus of elasticity, I is the least moment of inertia, and l is the length of the column.[1]

Increasing the length, therefore, weakens the resisting power of the column and increases the likelihood of fracture.

Cubes and short blocks tend to fracture at 45°, or somewhat less. But long columns, because of the preliminary flexure, split at a lower angle. In testing the strength of cast iron in engineering practice it has been found that, as the length of the longer dimension is increased while the other two dimensions remain the same, the angle of fracture becomes lower until it reaches 30°, beyond which there is no lowering with further increase in length.[2] Experimentation upon other materials has given analogous results.

The lowering of the angle in the long column is a result of the development of rotational strain. The preliminary flexing of the column develops tensile stresses on the outer side of the bend, and at the same time develops shearing stresses by which the layers on the outer side of the bend tend to creep toward the crest of the fold. This shearing of the layers may be illustrated by bending a pack of cards. If actual fracturing occurs, the effect of the rotational couple is to lower the angle of breakage.

Earth deformation theoretically may partake of the nature either of the short block or of the long column. Except for the influence of the curvature of the surface, in most cases it would seem to parallel most closely the short block, for the dimension of the mass involved parallel to the direction of thrusting is, as a rule, less than five times the transverse dimensions of the block. The Appalachian Mountain chain is at the very least 1,800 miles in length, paralleling the Atlantic Coast. To be five times this, the northwest-southeast dimension (the length of the flexed column) would need to be 9,000 miles, or completely across North America and much of Asia. From Cincinnati to Charleston, South Carolina, on the coast, which is a most generous estimate of the distance across the deformed belt, is only approximately 900 miles. The

[1] R. J. Woods, *op. cit.*, pp. 212–13.

[2] *International Library of Technology and Mechanics* (Scranton, Pa., 1909), pp. 2–3.

vertical dimension of the vigorously deformed Appalachian block is probably less. Very likely the column need not have yielded to the deformation throughout its entire length, and so the belt actually deformed may be less than the true length of the column, but one could not safely assign to such a hypothetical column a greater length than the width of the continent. The very long Cordilleran chain would make even greater demands in this direction. Mountain ranges with their long dimension paralleling coasts from which the thrusting is assumed to have come, and with a lesser transverse dimension in the line of the thrusting, are thus to be considered as short blocks. With still less of vertical thickness involved, they are perhaps more closely analogous to the deformation of a thin prism or wall.

It is possible, however, that very locally, in a portion of a mountain range, the conditions of the long column might be operative and low-angle faulting might result, but it hardly seems likely that this principle can, in any large measure, be responsible for the great overthrusts. The most that can well be claimed for it is that it may be a contributing factor.

Shape.—The shape of cross-section of deformed masses is a factor in determining the character of the deformation which results under stress. The strength of a column depends on whether the ends are free to turn, or are fixed and thus incapable of turning. Columns with round ends bend quite differently from those with square ends.[1] The shape of a lenslike mass of sediment, weaker or stronger than the surrounding rock, may well be important in determining the nature of the deformation which takes place when the mass is stressed.[2]

D. EFFECT OF ROTATIONAL STRAIN

As designated by Hoskins[3] and applied to structural geology by Leith,[4] strains due to compression are divided into two classes—rotational and non-rotational. Non-rotational strains are defined

[1] I. P. Church, *Mechanics of Engineering*, pp. 360–61.

[2] Suggested by T. T. Quirke, personal communication.

[3] L. M. Hoskins, "Flow and Fracture of Rocks as Related to Structure," *16th Ann. Rept. U.S. Geol. Surv.*, Part I (1896), p. 860.

[4] C. K. Leith, *Structural Geology*, pp. 16–21.

as those in which the principal directions of strain remain constant with reference to the principal axes of stress throughout the deformation. Rotational strains are those in which the axes of strain are being constantly rotated with respect to the axes of stress during the deformation. The behavior of a body deformed under each of these types of strain has been admirably set forth by Leith by the use of the strain ellipsoid and the wire-netting model. As shown in Figs. 5, 6, and 7 of his *Structural Geology*, the planes of no distortion are the planes of maximum shear, and are the planes along which fracturing should tend to take place in either rotational or non-rotational strain.[1] But the inclination of these planes of shear with respect to the applied force is different in the two cases. Under non-rotational strain the shearing planes are seen to be located approximately at 45° to the direction of the applied force. Under rotational strain, on the other hand, while the relation of the shearing planes to the strain ellipsoid remains the same, the position of these planes with reference to the direction of applied force is steadily changed by rotation. In the extreme case (pure shearing) one plane of shear is seen to be parallel to the direction of the force, while the other commences at 90° to the force and is gradually lowered in angle as the deformation progresses. Fracturing is more likely to occur in the plane parallel to the force than in the one highly inclined to it.

Thus the shearing plane inclined 45° to the force in pure non-rotational strain and the corresponding shearing plane parallel to the force in extreme rotational strain may be taken as the limiting cases. It is clear that between these two limiting cases of 45° and 0° fracturing may actually take place at any intermediate angle, depending upon the relative strength of the rotational and non-rotational factors. This will perhaps be made clearer by Fig. 7.

Ellipse *A* represents the cross-section of a sphere deformed by pure non-rotational strain resulting from a uniform, horizontal compressive stress. Shearing and fracturing may occur along either of the 45° shearing planes, but more likely along plane *b* than plane *a*. In ellipse *B* the force, though still horizontally directed,

[1] C. K. Leith, *Structural Geology*, pp. 18–21.

is not uniformly distributed, but is represented as somewhat stronger at the upper end than at the lower, as indicated by the relative length of the arrows. The fracture plane (*b*) in consequence of the rotation of the ellipse is inclined at approximately 40° to the force. In ellipse *C*, with stronger rotation, the active shear plane (*b*) has been lowered to an angle of 25°. In ellipse *D*, because of still stronger rotation, the fracture plane is only 15° from the horizontal, and in *E*, the limiting case of extreme rotational strain, the shearing plane has reached horizontality.

Applying these principles to the earth, horizontal thrusts may therefore theoretically produce shearing planes at any angle from 45° down to horizontality, depending upon the relative strength of the rotational element in the strain. Actual faulting, however, would probably not take place exactly in these planes of maximum shear, but would, as shown on pages 17–19, be modified somewhat further by the component of stress acting normal to the shearing plane. A marked rotational strain derived from horizontally directed stresses, if it can be shown that such are likely to be developed with sufficient frequency in earth dynamics, may form a working hypothesis to explain the great low-angle overthrusts. It therefore becomes necessary to seek the conditions which might result in the development of such strongly rotational strains.

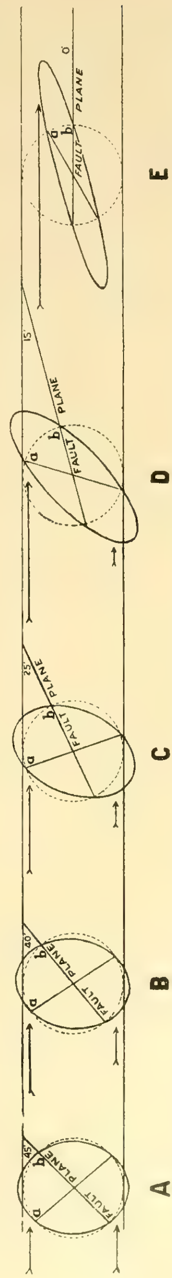


FIG. 7.—Theoretical deformation of a sphere by compressive stress. Ellipse *A*, representing the cross-section of a sphere deformed by pure non-rotational strain, is the limiting case at one end. The planes of no distortion (fracture planes) are here inclined at 45°. Ellipse *E*, representing extreme rotational strain, is the limiting case at the other end. The active shear plane (*b*) is here horizontal. Ellipses *B*, *C*, and *D* represent cases intermediate between the two limits.

1. *Rotational Strains Developed by Bedding*

In the explanation worked out by Hayes for the Rome and Cartersville overthrusts of the southern Appalachians, the most important condition necessary for the development of such broad thrusts is stated to be the proper relation of rigidity of strata to superincumbent load.[1] An idea of the relative rigidity of the different strata in this portion of the Appalachians may be obtained from an inspection of the stratigraphic column. At the base of the exposed section are the Coosa shales which have a great, but unknown, total thickness and a minimum rigidity. Above these are several formations (Weisner quartzite, Rome sandstone, and Connasauga shale) of intermediate rigidity. These are then followed above by the Knox dolomite, a formation of unusual rigidity which consists of 3,500 to 4,500 feet of massive, cherty, dolomitic limestone almost wholly without bedding planes. Immediately upon this rest 1,200 to 1,800 feet of rigid Chickamauga limestone whose lower portion is nearly as massive as the Knox. There are, in these two formations, approximately 5,000 feet of strata with indistinct bedding and entirely without beds of shale. This gives them great competency when subjected to deformative stress. Above the Chickamauga limestone are several thin formations of lesser strength, followed by 2,500 feet of very weak Floyd shale. This very weak series is followed in turn by several formations of greater rigidity, namely the Oxmoor sandstone, Bangor limestone, and Coal Measure sandstone. This section may be generalized as follows:

D—Moderately strong sandstones and limestones.

C—Weak shales.

B—Very rigid, massive dolomites of greath strength.

A—At base very weak shales.

It is the great competency of the thick dolomites, operating in conjunction with the incompetent beds above and below, which has controlled the deformation according to Hayes.[2] Quoting from Hayes's explanation of his diagram (see Fig. 2):

As already stated, the rigid mass *B* presents its weakest points where the compressing force exerts a shear across the beds—i.e., on the sides of the folds

[1] C. W. Hayes, *op. cit.*, pp. 150–52. [2] *Ibid.*, pp. 142–44.

H and L. But the point H is in the line of least resistance, since it is nearest to the region of application of the compressing force, and hence the mass of material to be moved is less than if the break were to occur at L. After passing the central rigid mass the line of least resistance follows the upper bed of minimum rigidity C till another fold is reached where it passes through the upper rigid bed D. Erosion of the latter might determine the point at which the line would emerge at the surface.[1]

The requisites of this type of overthrust are thus seen to be an alternation of formations of pronounced difference in competency, affected by slight folding and possibly by moderate erosion of the upper competent layer on the anticlines before the faulting commences.

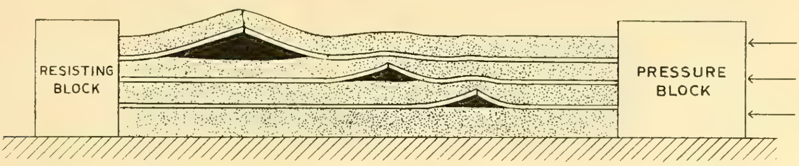


FIG. 8.—Arching up of competent layers when there is too much difference in the strength of the layers. The competent layers were composed of pure plaster, the weak layers of damp sand.

Experimentation: A single strong layer amid much weaker material.—To test experimentally some of these conclusions relative to the influence of a marked difference in the competency of neighboring layers upon the nature of their deformation, the crushing machine was loaded in the first set of tests with a single heavy, competent layer of plaster in the midst of weaker sandy layers above and below. When pressure was applied, the strong layer which carried most of the thrust commonly warped upward into a very low swell and then cracked at the top of the swell. With further compression the broken beds continued to arch up, leaving an open space below (Fig. 8). It did not appear to make much difference in its effectiveness whether the strong brittle bed were the top layer, or whether it were lower down in the series. If lower down and it was sufficiently competent, it still controlled the deformation and carried up the overlying weaker material with it.

[1] *Ibid.*, pp. 151–52.

Several strong layers between very much weaker ones.—When there were several strong layers between much weaker ones, similar arching was sometimes the result, if there was sufficient difference in the rigidity of the layers. But rather more commonly a strong tendency to dovetail was manifested. The strong and brittle beds of plaster were first thrust faulted, but in some cases the planes of faulting dipped toward the moving pressure block and in other cases away from it, thus giving both underthrusting and overthrusting (Fig. 9). After faulting commenced, the broken ends of the strong layers were wedged into the adjacent softer material, pushing it aside. Further compression caused an interwedging of

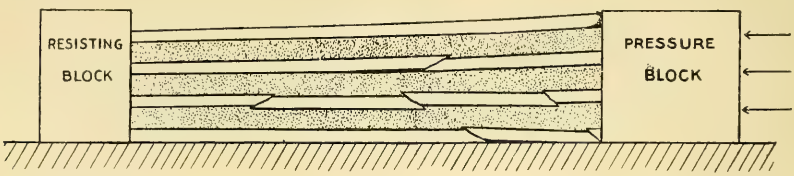


FIG. 9.—Development of dovetailing structure by both overthrusting and underthrusting when there is too much difference in the competency of the layers. With further compression the dovetailing becomes more pronounced. The strong layers were composed of four parts of clay and one of plaster; the weak layers were of damp sand.

the competent beds, producing a dovetailing structure. Dovetailing therefore results when there are a number of strong layers and the layers are too unequal in competency. This is commonly the case when there is an alternation of plaster layers and layers of damp sand. It even takes place when the competency of the strong layers is reduced by adding four parts of clay to one of plaster. This seems to be because the sand is very incoherent. When dovetailing does occur in experimentation, obviously not much is to be learned from the results so far as the present problem is concerned.

Less difference in competency.—The conditions of the last set of experiments apparently do not at all approach the conditions which control faulting in the earth. There was too great difference in the relative strength of the layers. The weak layers were too weak. For the next set of experiments sand was abandoned and only

mixtures of clay and plaster were used. Fairly good results were obtained by making the stronger layers of equal parts of plaster and clay and the weaker layers of one part of plaster to two parts of clay. There was then a working difference in competency, but at the same time not too great a difference to cause simple arching or the troublesome dovetailing.

Fracturing was found to take place at different angles across different beds. In general, it followed lower angles across the softer layers than across the stronger and more brittle ones. Perhaps the most typical result obtained is shown diagrammatically in

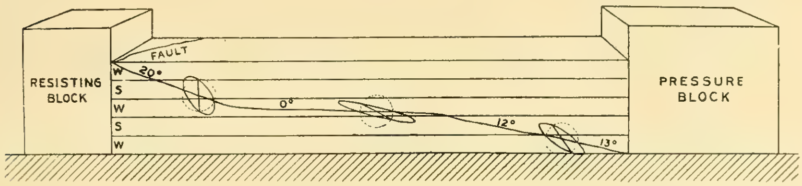


FIG. 10.—Drawing of experiment which shows how the inclination of the fracture plane may vary greatly in crossing beds of different competency. Because of the operation of a rotational strain following the fracturing of the brittle competent layers, there resulted nearly horizontal shearing through the weak, clayey layer. The strain ellipses are drawn upon the fracture line to illustrate the variable nature of the strain.

Strong layers (*S*) composed of equal parts of plaster and clay; weak layers (*W*) of one part plaster and two parts clay.

Fig. 10. When pressure was first applied in this experiment, the stronger layers carried most of the thrust, while the softer layers yielded and accommodated themselves so far as was necessary by compacting. With increasing strain the upper strong layer fractured at an angle averaging 20°, and this plane of fracture was projected through the overlying clay. With this fracturing a strong rotational strain developed below. This caused almost horizontal shearing through the soft clayey layer, where the prevailing angle of the fault plane is found to be less than 5°, and as a result of these shearing stresses the strong plaster layer below was faulted at 12°.

Bedding, therefore, where there is sufficient difference in the relative competency of the strata, may be an important factor in

determining low-angle faulting. As shown in Fig. 10, in which the ellipsoids representing the axes of strain are drawn upon the beds, the lowering of the angle in this way seems to be the result of shearing stresses and rotational strain. A difference in competency is thus one means of developing rotational strain, and the type of faulting described above comes under the category of rotational strain thus produced. The difference in competency may not be solely because of a difference in the kind of rock, but it may result also from a very unequal distribution of bedding planes which are planes of weakness. It is to be noted that an abundance of strongly marked, closely spaced bedding planes, in addition to making the competency of the formation less with respect to more massive adjacent formations, also makes splitting parallel to the bedding of the bedded rocks much easier than breaking across the bedding. With less resistance offered in that direction, fault planes crossing very thin bedded shales will be lowered to a certain extent toward parallelism with the bedding. The more bedding planes and the more pronounced they are, the lower the angle of faulting.

General discussion.—The Lewis overthrust in the Glacier National Park of Montana, according to the well-known explanation of Willis, who would classify it as an erosion thrust, appears to be a case of low-angle faulting controlled by bedding.[1] The fault plane, where observed, is located in the Proterozoic Altyn limestone, whose bedding it appears to parallel closely. Above the fracture plane, for the most part, are rigid, brittle, competent strata. What lies below the fault plane is not known, since the oldest formation in the vicinity is the Altyn limestone just above the fault plane. This has been overthrust upon the Cretaceous. In the explanation given by Willis, the sequence of events is, first, gentle folding by which there was developed a low, unsymmetrical anticline whose gentler west limb had a nearly constant westerly dip. Erosion then removed the crest of the fold, thus leaving the west limb a thick sheet of competent strata, unweakened by secondary flexures

[1] Bailey Willis, "Mechanics of Appalachian Structure," *U.S. Geol. Surv., 13th Ann. Rept.*, Part II (1893), p. 223 and Pl. LIV, Figs. 6 and 7; "Stratigraphy and Structure, Lewis and Livingston Ranges, Montana," *Bull. Geol. Soc. Amer.*, XIII (1902), 331–43.

and in a position to carry thrusts from the west. Because of the erosion of the crest of the anticline, support from the east limb had been to a considerable extent removed, and frontal resistance to a thrust from the west greatly reduced. With resistance in front lessened and resistance beneath unchanged, or very much less diminished, lateral thrusts developed shearing stresses which caused the overthrust. This type would, therefore, be an overthrust due to rotational strain fostered by the special attitude of the strata and especially by the lessening of the resistance to a forward movement of the upper layers because of preceding erosion. The shearing then took place along a bedding plane as a line of weakness.

The pretty structural explanation of the southern Appalachian overthrusts offered by Hayes was entirely dependent for its working qualities upon appropriate stratigraphic formations of widely different competency. Similarly, though to perhaps lesser degree, the erosion-thrust of Willis is dependent upon appropriate stratigraphy and antecedent history. Admitting that each of these explanations fits the particular case, or type of cases, for which it was devised (which was probably all that the authors intended), it is clear that an explanation on either of these lines cannot fit the type of overthrust which is so wonderfully displayed in the Scottish Highlands. In these remarkable dislocations the low-angle overthrusting did not occur until after the continuity of bedding over the overthrust area had been completely interrupted and displaced by repeated slice faults at the ordinary angle of 40° to 45°. The Scottish overthrusts did not follow any one weak formation, as did the overthrusts in the southern Appalachians, but cut straight through the various rocks of many previously faulted blocks. It is clear that a more general *raison d'être* for low-angle faulting must be sought.

2. *Rotational Strain in Homogeneous Material*

Piling up of material a possible factor.—One of the most characteristic features of the Caledonian diastrophism which produced the faulted structure of the Scottish Highlands was the development of a remarkable imbricate structure prior to breaking along the great thrust planes. It seems to be well established, both from the field

evidence and from Cadell's experiments, that the order of events was first slice faulting of the ordinary 45° angle type, and that, after a mass of slices had piled up in this manner, a low-angle thrust plane broke through the mass of slices and the whole mass above rode bodily forward on this plane as a "sole."[1]

Similarly it will be observed that the well-defined Rome overthrust in the southern Appalachians occurred in the midst of a

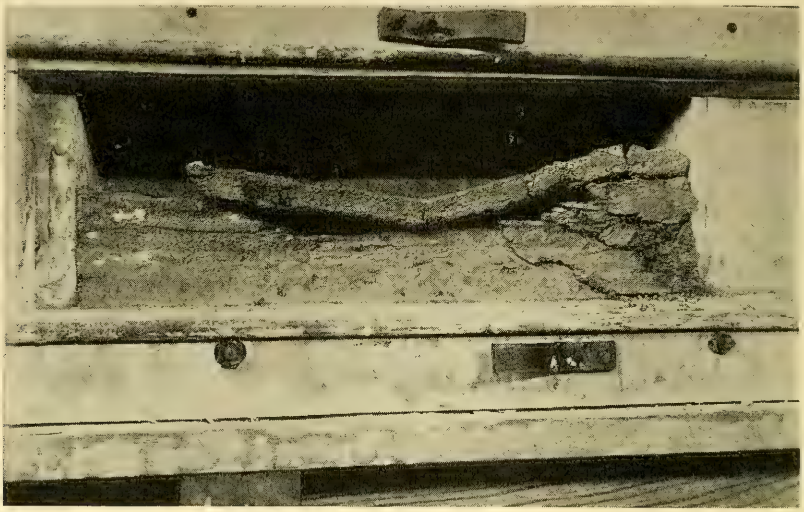


FIG. 11.—Slice faulting, developing an imbricate structure. The bottom layer was composed of pure clay; the next above of mixed sand and clay; the third was a thin layer of sand; and the heavy competent layer at the top was made of plaster two parts, sand one part and clay one part. The brittle top layer arched up and fractured as the first slice fault developed. Each successive slice fault broke out below and in front of its predecessor.

series of ordinary reverse faults. Directly south of the town of Rome, Georgia, there are mapped six large reverse faults just to the east of the line of the great overthrust. They are thus in the mass which traveled westward with the overthrust.[2] Similar slice faults in series, though they cannot be traced continuously into the par-

[1] J. Horne, "The Geological Structure of the Northwest Highlands of Scotland," *Mem. Geol. Surv. of Great Britain*, 1907, pp. 471–76; H. M. Cadell, *op. cit.*, pp. 347–48.

[2] C. W. Hayes, *U.S. Geol. Surv. Geol. Atlas, Rome, Ga.*, Folio 78, 1902. Structure Section Sheet.

ticular breaks near Rome, are especially numerous in the same relation to the overthrust throughout the southwest portion of the quadrangle. Somewhat analogous relations are to be noted elsewhere. Directly in front of the Lewis thrust in Montana there is represented on the structure sections a series of slice faults formed as if in preparation for another overthrust which presumably, if the deformation had been carried further, would have broken through lower than the Lewis slip and to the east of it.[1]

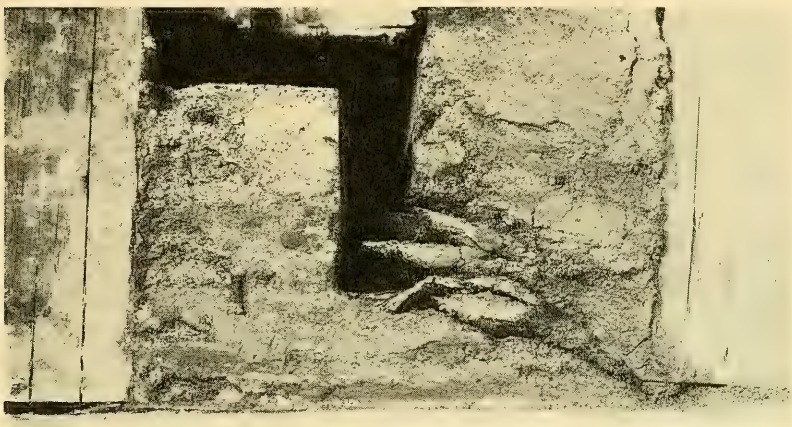


FIG. 12.—Deformation of specially shaped mass. Slice faulting resulted. In this particular experiment the pressure blocks were not held rigidly in place by controlling flanges, but were free to rise or become tilted.

A relationship between a piling up of rock masses and the development of the low-angle overthrust has therefore been suggested. It might at first seem possible that lateral thrusting applied upon the piled-up mass, thus bringing forces to bear in a higher plane than would be the case if there were no piling up, would, on the lever-arm principle, develop a rotational strain which would cause fracturing at a lowered angle. To test this question experimentally, there was molded in the box a homogeneous mixture of clay and plaster, which was high adjoining both pressure blocks and low in the middle. The rectangular

[1] Eugene Stebinger, "Geology and Coal Resources of Northern Teton County, Montana," *Bull. 621*, *U.S. Geol. Surv.*, 1916, Pl. XV.

outlines of the prepared block, by exaggerating any case of piling up likely in nature, ought not to fail to reproduce the low angles, if such be due to piled-up material acting in this way. The results are shown in Figs. 12 and 13. There was first slice faulting on the right-hand side, from which the pressure came. Each successive fault broke below the previous one as the mass was compressed more and more. This is similar to the experience of Cadell. As compression went on, the planes of the earlier faults became

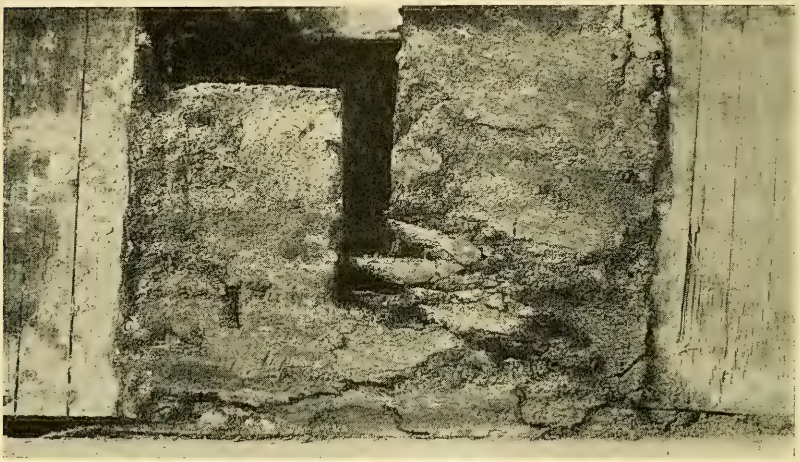


FIG. 13.—Same as Fig. 12. After further compression

distorted and obscured by the later deformation. At length a low-angle fracture broke through from the left, or resistance block side. This was no doubt determined by lines of least resistance due to weakening by the previous fracturing.

To test the matter further a mold of pure paraffine was prepared in essentially the same shape. The paraffine had the advantage of being more nearly homogeneous than the clay-plaster combination. In the two trials made, fracturing proceeded directly across the elbow at approximately 45° (Fig. 14). Lest the right-angled elbow might play an unsuspected part in determining the angle of splitting, paraffine was molded into a block having the shape shown in Fig. 15. When pressure was applied the block faulted at the farther end. It faulted at the farther end because

the force per square inch was greater there (owing to the smaller cross-section over which it was distributed) than at the other end near the pressure block where it was distributed over a larger area of cross-section. Rupture occurred where the intensity of stress was greatest, even though it was farthest removed from the pressure block. The fault averaged 42° for its whole length. The angle shows that it was caused by a non-rotational strain. The same was true also of the two previous tests. The shape of the block, at least to the extent of the variations tried in these experiments, apparently does not change the nature of the strain. But perhaps, after all, only a non-rotational strain could develop under

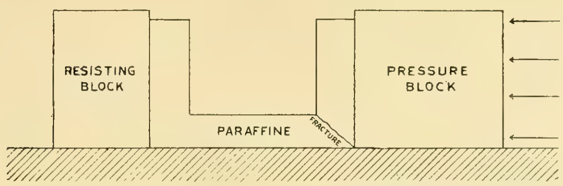


FIG. 14.—Block similar in shape to that shown in Figs. 12 and 13, but composed of paraffine. A 45° fracture developed.

the conditions of these experiments, since the pressure block is guided rigidly forward by the controlling flanges of the machine and so cannot turn. But one may conclude, nevertheless, that a piled-up mass having a higher standing cross-section to be pushed forward, does not, of itself, add a rotational element to the strain when laterally compressed, nor, so far as this principle is concerned, does it lower the angle of fracture.

How rotational strain develops fracture.—To show how a rotational strain will deform such a block as was used in the experiment just described, another block of paraffine was cast in the same mold and subjected to a rotational strain in the following manner. As before, the pressure was applied from the same long side, but instead of being applied against the whole surface of that side it was applied only to the upper half of it. The resisting block, as before, buttressed the whole of the shorter left-hand side. With the opposing forces acting horizontally at quite different elevations, a rotational couple was developed. As the strain slowly increased the paraffine

near the pressure block first yielded somewhat by plastic deformation. Then, as a result of the shearing stresses, it started to break along a very low angle of fracture near the bottom of the block (Fig. 16, break *A*). The experiment was stopped at this point and the block removed for study. After a rest of a few days the deformed block was again placed in the crushing machine and

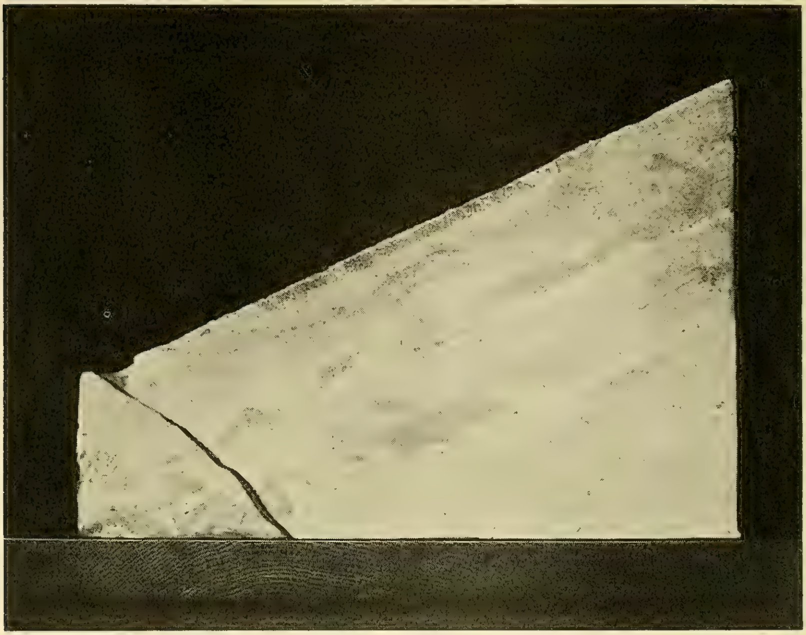


Fig. 15.—Deformation of specially shaped paraffine block under non-rotational strain. Pressure applied uniformly upon right-hand face. Fracture averages 42°.

pressure applied as before. But instead of further splitting along the old line of breakage near the bottom of the block, an entirely new break occurred at a much higher level (Fig. 16, break *B*). This new fracture extended completely across the block. Though irregular in detail, its general direction was very close to horizontal. To verify these results, a new block of paraffine was cast in the same mold and pressure was again applied in the same way. The result again was breakage along a nearly horizontal shearing plane (Fig. 16, break *C*). In breaking out at the surface, however, the fault plane,

in both cases, turned upward, producing a considerably steeper angle in the immediate vicinity of the surface.

Experiments therefore show that the effect of a strong rotational strain, even in homogeneous material, is to produce shearing and complete rupture, essentially parallel to the direction of the applied force. If the thrusting be in a horizontal direction, the plane of rupture will approach horizontality. In these experiments it was noted that the low-angle shearing required fewer turns of the screw and thus the application of less force than the 45° fracture from

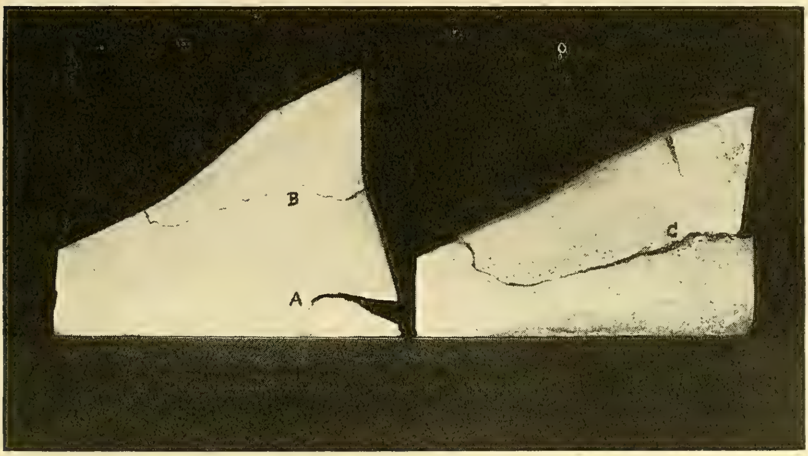


FIG. 16.—Deformation of paraffine blocks (same mold as block in Fig. 15) under rotational strain. Pressure applied only to the upper half of the right-hand face. The fracturing, though irregular, was not far from horizontal.

non-rotational strain. This merely bears out the well-known fact that the resistance of materials to shearing stresses is much less than to direct compressive stress. Hence the disposition to shear if conditions allow.

Lessening the resistance above.—Deformation by rotational strain may thus be developed in homogeneous material by sufficiently increasing the effective differential stress in the upper portion of the mass with respect to that in the lower portion. It is the greater unbalanced pressure in one portion over another which is effective. This unbalancing of pressure may be accomplished in several ways. Within the earth it may be produced either by increasing the lateral

thrusting in the upper portion or by lessening its resistance, while the lower portion remains unchanged. It may also be developed by diminishing the thrust below or by increasing the resistance in the lower part, while conditions in the upper portion remain essentially the same. Or it may be accomplished by some combination of these. The first process facilitates deformation in the upper part; the second retards deformation in the lower part. Whatever affects the ratio influences the character of the deformation. The greater the difference developed the greater the shearing tendency. The intensity of thrusts and the resistance at different horizons in the earth should therefore be a vital factor in determining shearing.

At the present time the location and intensity of lateral thrusts in the earth are so imperfectly understood that a treatment of that topic is reserved for further information. Rather more, however, is known concerning the resistance offered. Factors which either lessen the resistance above, or increase it below, may play a part in overthrust faulting.

The resistance above may be diminished in several ways. The erosion-thrust of Willis and Hayes already discussed is a clear-cut illustration of how it may be accomplished in heterogeneous materials. Resistance above is here reduced by erosion which removes the heavy, competent upper layers from the crest of an anticline. The resistance of the remnants of the upper layers to forward movement having been sufficiently diminished in this way, this more movable portion shears nearly horizontally along a bedding plane as a line of weakness (see Fig. 2). Shearing along bedding planes and the control of overthrusts by differences in the competency of the beds are related phenomena.

In homogeneous material the resistance above is lessened by other means. The experiments of Cadell indicated that before the low-angle overthrust occurred there was first slice faulting and the piling up of slices. Slice faulting to a remarkable extent was associated with the Scottish overthrusts and to a certain extent with those in the southern Appalachians. If the mere piling up of materials, as such, does not introduce a rotational element to the strain and so lower the angle of fracture, nevertheless the repeated slice faulting and moving of fault blocks do have an effect upon

the resistance of the faulted strip. The slicing and secondary shattering would seem to weaken the superficial sheet which has suffered the faulting. It may be perhaps that the superficial shell, freer to move as a general mass than it was before slicing, while the lower, deeper levels have not been equally affected by what has taken place, now finds it easiest to slide bodily forward over the less movable lower portion. If this be true, it would make the rupturing by the preparatory slice faulting far more important in the development of low-angle overthrusts than the piling up of material.

Greater resistance and drag below.—With horizontally directed compressive stresses in operation rotational strains would also tend to be produced by the co-operation of any factor which increased the resistance of the deeper portion of the rock mass involved, while the resistance of the more superficial portion to such stresses remained the same. The far-reaching experimental studies of Dr. Adams and his colleagues have shown that, on account of the increasing rigidity of the rocks due to cubical compression from the weight of overburden, resistance to deformation in the earth should increase with increasing depth below the surface.[1] It is concluded that with increasing depth greater and greater stress differences are required to deform the rocks. From this principle it would seem to be a legitimate deduction that, for a lateral thrust of given magnitude, rock deformation should take place more readily near the surface of the earth than at a greater depth beneath the surface, and that in any case (barring the effects of local heating, or liquefaction) deformation should become less with depth, unless the magnitude of the stress differences which cause the thrusting increases as rapidly with increasing depth as does the resistance offered by the rocks.[2]

[1] Frank D. Adams, "An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust," *Jour. Geol.*, XX (1912), 97–118.

[2] Since this was written, the principle of increasing resistance to deformation with depth below the surface of the earth has been strongly affirmed by Adams and Bancroft as the result of further experimental researches. (See Frank D. Adams and J. Austen Bancroft, "On the Amount of Internal Friction Developed in Rocks during Deformation, and on the Relative Plasticity of Different Types of Rocks," *Jour. Geol.*, XXV [1917], 597–637. Also Louis Vessot King, "On the Mathematical Theory of Internal Friction and Limiting Strength of Rocks under Conditions of Stress Existing in the Interior of the Earth," *Jour. Geol.*, XXV [1917], 638–58.)

In general, so far as these principles hold, there should be a tendency, strong or feeble according to the quantitative factors, for surficial shearing over a less movable portion below. Rotational strains thus brought into being might conceivably in some cases be a primary cause of low-angle shearing, or in other instances might co-operate as a secondary factor with other more important causes in producing a similar result.

Many glaciers, notably those in North Greenland, have developed in places horizontal shearing planes which are often grouped into distinct zones.[1] The englacial drift is definitely arranged along these planes of movement, and this in turn influences the rate of melting on the steep edge of the glacier, so that these planes of shear have, in many instances, become very conspicuous. These lines of débris are especially prominent in the lee of an embossment of rock over which the glacier has just passed. In most cases the shearing planes may be interpreted as due to the greater resistance of the rock knobs below. They seem to be further developed by the increased load of débris in the lower part of the glacier and by drag on the bottom beneath the moving mass. The rotational strain thus engendered causes nearly horizontal slippage of the upper portion over the lower. Where formed in the lee of an embossment of rock another factor enters to increase the rotational element. The rock mass protects the lower portion of the glacier from much of the push which the upper portion is receiving.[2] Thus while the upper portion of the ice is free to move forward, not only is the resistance of the lower portion of the ice to forward motion increased, but at the same time the actual thrusting to which that portion is subjected is diminished.

C. E. Decker has described various minor folds and small thrust faults, mostly of Quaternary age, which affect the strata close to the surface in northeastern Ohio and northwestern Pennsylvania.[3] The fault planes of these thrusts are commonly inclined at low angles (Fig. 17). If their proximity to the surface is of real

[1] T. C. Chamberlin, "Glacial Studies in Greenland," *Bull. Geol. Soc. Amer.*, VI (1894), 203–10.

[2] T. C. Chamberlin, *op. cit.*, pp. 207–8.

[3] Charles E. Decker, unpublished manuscript.

significance, it would suggest a strong tendency of layers near the surface to shear over less movable layers below.

E. EFFECT OF WEIGHTING

Although the piling up of faulted slices does not of itself cause the development of rotational strain, when the mass is subjected to horizontal compression, it may indirectly bring about that result by weakening the resistance of the upper portion owing to the

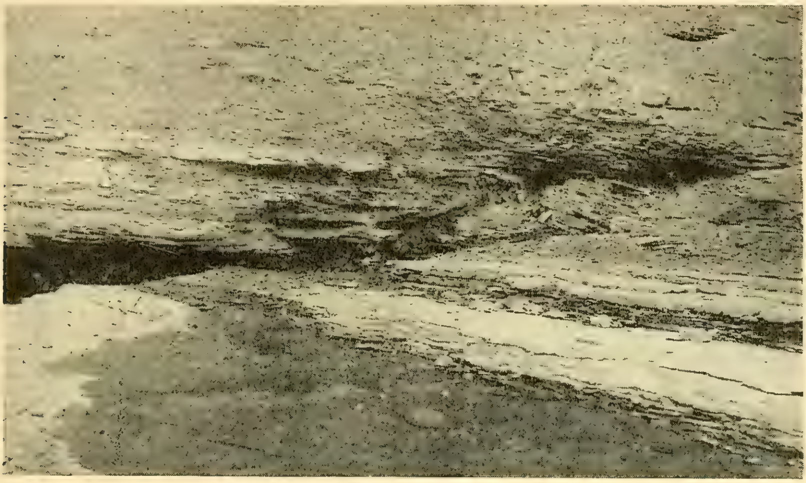


FIG. 17.—Thrust fault in Chagrin shales. On Paine Creek, 6 miles east of Painesville, Ohio. Fault plane dips 15° S.W. Throw 1 ft., heave 2 ft. 11 in. Charles E. Decker.

preliminary fracturing. If, in addition, the mass piled up is of sufficient magnitude, it may theoretically affect the result in another way owing to the fact that the additional weight of the piled-up mass adds a new force at right angles to the horizontal thrust. Figure 18 will illustrate the behavior of this force. In this diagram the horizontal thrust was taken to be three times the vertical force due to gravity. The resultant of these two forces will be inclined downward 18° 26′ from the horizontal. Fracturing as the result of these two forces will be determined by the direction of this resultant of forces. As this is inclined 18° 26′ downward from the horizontal, faulting, even though it should take

place at an angle as high as 45° upward from the resultant of the forces, would still be only 26° 34′ from the horizontal. The relative magnitude of the horizontal thrusting force and the weight of the heaped-up mass determines how much the angle of faulting, under the given conditions, will be diminished from 45°. If the weight of the load gave a force equal to half that of the lateral thrust, the angle would be lowered because of this factor to the extent of 26° 34′, thus making it 18° 26′ from the horizontal. If the vertical force due to the extra load amounted to one-fourth the horizontal thrust, the angle of faulting would be lowered approximately 14° 2′, leaving it 30° 58′ from the horizontal. The resulting angle for the various stress ratios may readily be calculated.

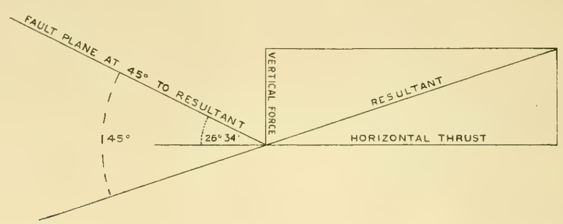


Fig. 18.—Diagram to illustrate the position of a fault plane inclined 45° to the resultant of forces. The horizontal thrust is here taken to be three times the vertical force. Result: the fault plane will be inclined 26° 34′ from the horizontal.

The effect of adding load, and hence additional force acting downward, is to subject the material under thrust to increased cubical compression. According to the principles so strikingly worked out by Adams and his colleagues, the effect of this should be to increase the internal resistance of the material and thus necessitate a much greater stress difference to initiate deformation than would be required without the additional load. Greater stress difference necessitates much greater lateral thrusts. As a result faulting may be hindered or even prevented altogether until much greater thrusts are developed. It may also, in consequence, be caused to take place elsewhere, as, for example, some distance beyond the edge of the loaded area. In our experiments with weighting the faulting most frequently appeared at the surface close to the border of the weighted portion, the fault plane dipping

under the heavily burdened portion (see Fig. 19). But in these experiments the loads were relatively light.

A load light in proportion to the horizontal stress will thus influence the angle of fracture, depending upon the ratio of vertical and horizontal stresses. A load very great in proportion to the horizontal stress will prevent faulting altogether within the loaded area. The influence of the load upon the angle of thrusting will therefore reach a maximum value somewhere between a load which

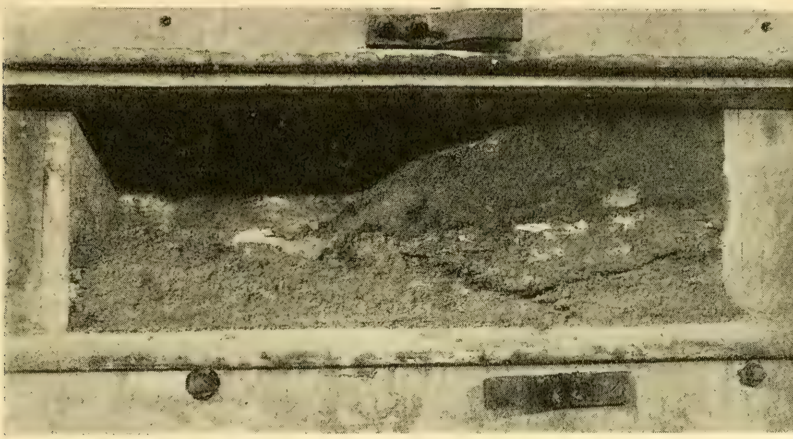


FIG. 19.—Effect of local weighting in locating the position of faults. The material to be faulted was clay stiffened with plaster; the added load was damp sand. In experiments of this sort the fracture plane most frequently appeared at the surface close to the edge of the piled-up overburden.

is light and a load which is heavy relative to the horizontal stress. What the proper ratio for the maximum effect will be cannot well be determined until more is known of the limiting strength of rocks under stress.[1] Some idea, however, may be gained possibly by a rough inspection of the factors involved. The stress difference necessary to cause faulting at a given depth in the earth would need to be sufficient to exceed the sum of the crushing strength of the given rock at the surface, plus the weight of overburden which must be lifted, plus again the increased strength of the material

[1] Louis V. King, "On the Limiting Strength of Rocks under Conditions of Stress Existing in the Earth's Interior," *Jour. Geol.*, XX (1912), 119–38.

resulting from the compression under the load. Suppose there were 10,000 feet of rock piled up above the plane along which the fault is to occur. Assuming a specific gravity of 2.7 for the rock, the pressure resulting from this column will amount to about 11,760 lbs. per square inch. If the stress along the axis of greatest stress, which is here horizontal, be taken to be three times this, it would need to be 35,280 lbs. per square inch. As the axis of least stress is vertical, the stress difference would amount to 23,520 lbs. per square inch. To cause faulting, this stress difference must equal the crushing strength of the rock under surface conditions augmented by the increased strength of the material induced by the hydrostatic pressure or cubical compression. This increased strength because of the depth is considerable, but pending more work of the type carried on by Adams and his colleagues this is not easily evaluated.[1]

However, this stress difference clearly would not be sufficient at this depth to deform the stronger rocks, like granite, and probably not rocks of average strength, though very likely it would be sufficient to deform the weaker rocks. Under these conditions, if the horizontal thrust were less than three times the vertically acting force, the stress difference would be proportionately still less effective in deformation. A ratio of more than three to one would, on the contrary, be more effective. A ratio of thrust to the weight of not less than three to one would seem to be required for extensive faulting through rock formations of average strength under a load ranging up to 10,000 feet of rock. This might lower the angle of faulting by 18° or less. But this reduction in angle from 45° falls far short of developing the approximately horizontal slippage planes of the great overthrusts. With loads greater than 10,000 feet of rock, the resistance of the underlying rock is still further increased. While the increase in resistance probably does not mount up in direct proportion to the increase in balanced pressure, nevertheless for any thicknesses of rock likely to be piled up by diastrophic agencies there probably would not be a very radical change in the ratio of axes of stress necessary for faulting. At

[1] More data are now available. See Frank D. Adams and J. Austen Bancroft, *Jour. Geol.*, XXV (1917), 597–637; also Louis Vessot King, *ibid.*, XXV (1917), 638–58.

best only a part of the lowering of the angle from 45° can be explained in this way.

If the low angle of the great overthrusts were solely a matter of load steadily accumulated by piling up slice fault blocks, then each successive slice fault should break through at a progressively lower angle. There should be a complete gradation from the first-formed fault near 45° to the final overthrust approaching horizontality. While some progressive lowering of the angle of the successive slice faults is to be noted in some Scottish Highland sections and elsewhere, nevertheless there appears to be a great final jump from the minor slice faults to the great horizontal overthrust.

F. RÉSUMÉ

The great overthrusts which are now coming to be recognized as a prevalent and commanding type of mountain structure are the result of conditions differing considerably from those which produce ordinary reverse faults. The distinguishing features of the overthrusts are the extremely low angle, which often approaches horizontality, and the very great displacement along the plane of slippage. The great displacement is made easier by the gentle slope of the fault plane. The low angle of the fault plane is the net result of the operation of several factors. Among the factors which will lower the angle of faulting from the theoretical 45° may be listed the following:

1. The normal or direct stress which, along planes inclined 45° to the line of application of the force, has an intensity as great as that of the tangential stress. It acts as a frictional resistance to shearing by the tangential stress. The lower the angle of the fracture plane, the less will be the frictional resistance due to the normal component of the stress. Hence the tendency to fracture at angles below 45°.

2. Rotational strain, which will lower one of the planes of no distortion (shearing plane) from 45° in pure non-rotational strain to 0° in the extreme case of rotational strain. Rotational strains may be developed from horizontal compressive stresses: (*a*) in homogeneous material: (1) by any factors which will increase the intensity of the tangential stress in the upper portion of the mass

undergoing thrusting with respect to that in the lower portion; (2) by any factors which will lessen the resistance in the surficial portion without proportionately changing that below; and (3) by any factors which will increase the resistance of the deeper portion of the zone subject to thrusting while the upper portion remains freer to yield; (*b*) in heterogeneous material by bedding, or similar structures, which present differences in competency of the right sort and thus call into operation some of the foregoing factors.

3. Preliminary piling up of material in the first stages of deformation, thus increasing the load and the vertically acting gravitative force. The combination of the horizontal thrusting force and the vertical gravitative force gives a resultant which is inclined downward from the horizontal. Even should faulting take place in a plane 45° from this resultant, it would still be inclined less than 45° from the horizontal.

4. Possible minor factors, as heterogeneity of material, length of deformed mass with respect to its other dimensions (after analogy of long column), shape of deformed mass, etc.

To these factors, operating in various combinations according to the individual peculiarities of each particular case, are attributed the low-angle fault planes of the great overthrusts.

THE HART MOUNTAIN OVERTHRUST AND ASSOCIATED STRUCTURES IN PARK COUNTY, WYOMING[1]

C. L. DAKE
Tulsa, Oklahoma

INTRODUCTION

Field work during the summer of 1916 brought to light what is believed to be one of the most interesting major thrusts yet described in the northern Rocky Mountains. So far as the writer is aware, the true nature of this fault has not heretofore been described, although Fisher[2] refers to it in discussing the structure of Hart Mountain. The area studied embraces a narrow strip of territory lying between the area covered by Fisher's Big Horn Basin report, just mentioned, and the Absaroka quadrangle on the west.

STRATIGRAPHY

The stratigraphy of the region is essentially the same as that given by Fisher in his above-mentioned paper describing the area adjacent on the east. The divisions of the Cretaceous adopted in mapping are those used by Lupton,[3] since they represent more detailed work than was done by Fisher. Hewett[4] has also described the stratigraphic column in some detail in the region immediately east of the area mapped by the writer. The following table of formations is largely compiled from the three reports mentioned above. Detailed description of the various stratigraphic units will not be given, except in the case of the so-called Fort Union(?) regarding the age of which there may be some question.

[1] Published by permission of the Wyoming State Geologist.

[2] C. A. Fisher, *U.S. Geol. Survey, Prof. Paper No. 53*, p. 37.

[3] Lupton, "Oil and Gas near Basin, Wyoming," *U.S. Geol. Survey, Bulletin 621L.*

[4] Hewett, "The Shoshone River Section," *U.S. Geol. Survey, Bulletin 541*, pp. 89–113.

Fort Union(?).—Since there is some uncertainty as to the age of the formation described under this name, and since upon this formation more than on any other depends the dating of the fault in question, it seems worth while to give a detailed description of its relations and lithologic character.

TABLE I

TABLE OF FORMATIONS

System	Formation	Characteristics	Thickness in Feet
Quaternary....	....	Glacial till and terrace gravels	?
Tertiary......	....	Andesitic breccias and lavas	?
Cretaceous or Tertiary....	Fort Union(?)	Buff to yellow sandstones, conglomerates, red and gray shales	300+
Cretaceous....	Cody.........	Gray to black shale, sandy near top	2,000
	Frontier.......	Gray sandstones and shales, with bentonite	500
	Thermopolis and Mowry..	Gray and intensely black shales, with sandstone and bentonite	900
	Cloverly.......	Gray cross-bedded sandstone and shales	110
Jurassic or Cretaceous..	Morrison......	Variegated red, gray, maroon (etc.), shale, and sandstone	500
Jurassic.......	Sundance......	Greenish-gray shales and sandstones and thin fossiliferous limestones	500
Permo-Trias...	Chugwater.....	Red sandstones and shales with gypsum	750
Carboniferous..	Embar........	Massive gray limestone	100
	Tensleep......	Massive gray sandstone and brown quartzite	100
	Amsden.......	Red shale and red to gray limestone	150
	Madison.......	Massive gray limestone, conglomeratic at the base in places	1,000
Ordovician....	Bighorn.......	Massive gray limestone	300
Cambrian.....	Deadwood.....	Conglomerates, sandstone, and limestone	800
Pre-Cambrian.	....	Red granite, gneisses, and schists	?

It consists of an unmeasured thickness of alternating beds of yellow sandstone with red and white or gray clays. The sandstones vary from buff to bright yellow, and occur in several beds from 2 to 20 feet thick. They are cross-bedded on a large scale, and contain many concretions of brown sandstone varying from a few inches up to 10 feet or more in diameter. The concretions are harder than the matrix and weather out in large numbers, occurring abundantly over the surface of the ground. At many places the sandstones are finely conglomeratic, the pebbles averaging between one-fourth

and one-half inch in diameter. Red granite, basalt, quartzite, sandstone, black chert, brown chert, and shale make up the bulk of the pebbles. The shale members of the formation are dominantly gray, but contain many red layers. Thin lignitic seams were noted, but no leaves were found in a sufficient state of preservation to permit identification. One thin seam of black coal was found in the formation.

At one point the beds were seen to rest on the Cody with slight angular unconformity, although at several other points they partake of the folding of the older formations.

Though no fossils were found in these beds, the abundance of the red clays, the pebbly character, and the slight angular unconformity at the base all seem to favor correlation with what Hewett has called the Fort Union. It is true that Hewett has made no mention of the large concretions which are so abundant, and the writer noted similar ones from the basal Laramie of Fisher (Hewett's Gebo), not far to the east of the area mapped. At the same time similar concretions were noted, however, at a much higher horizon in Fisher's Laramie, in what is believed to represent Hewett's Fort Union. Fisher describes such concretions as occurring in the Laramie, but does not indicate the exact horizon.

Along the North Fork of Shoshone River these beds trace continuously into what Hague[1] has mapped as Pierre and Fox Hills. At the same point, however, Hewett[2] calls them "Tertiary sandstones and shales probably of Wasatch age." Structural reasons will be given later for believing that they are earlier than Wasatch.

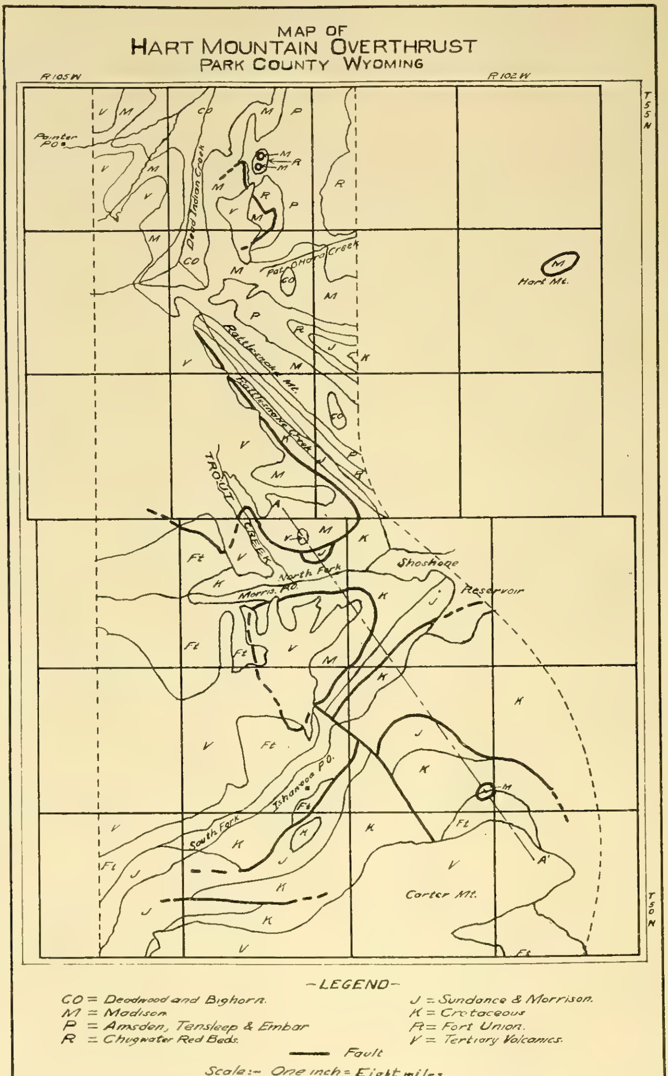
STRUCTURE

The major thrust.—The main plane of fracture occurs at or near the base of the Madison (Mississippian) limestone, which has been thrust out over beds varying in age from Madison to Fort Union(?). At the southernmost point, where the fault was located, the limestones rest on sandstones of Fort Union(?) age, but toward the north the stratigraphic throw decreases until at the northernmost

[1] Hague, Absaroka Folio, *U.S. Geol. Survey*, Folio 52.

[2] Hewett, "Sulphur Deposits in Park County, Wyoming," *U.S. Geol. Survey, Bulletin 450*, p. 478.

extremity the Madison rests on the Chugwater Red Beds. For the most part the Mississippian limestones are more resistant than



the beds on which they rest, and this condition results in a pronounced Madison escarpment along most of the course of the fault.

This escarpment is a very striking feature of the scenery along the Cody Road to Yellowstone Park, just west of the Shoshone Reservoir.

Traced westward up the valley the fault on either side passes beneath the Tertiary volcanics and is lost. It passes in a bold escarpment around the east end of the divide between the North and South forks of Shoshone River and extends for several miles up the north side of the latter valley, where it is again buried beneath the Tertiary breccias. It does not reappear on the south side of the valley of the South Fork except as an isolated peak of Madison resting on Fort Union(?) at the east end of Carter Mountain in Sec. 36, T. 51 N., R. 103 W. Several miles south of this point, however, abundant Madison bowlders are noted along the slopes on the east and southeast of Carter Mountain, indicating that the fault block of Madison probably occurs buried beneath the lavas of that mountain, or even possibly outcropping in small overlooked exposures along the lava scarp of that divide.

On the north side of the North Fork Valley the scarp makes a sharp re-entrant where Trout Creek cuts through the faulted block. In Sec. 6, T. 52 N., R. 103 W., the scarp bends abruptly northwestward and extends for a long distance along the west side of Rattlesnake valley, overlapped at several points by Tertiary volcanics, beneath which it passes at the head of the valley. In this distance the Madison rests on successively older beds, from Cody shale to Chugwater "Red Beds." The trace of the fault could not be found on the east side of Rattlesnake valley, from which the block of faulted Madison has probably been largely removed by later erosion. It is suspected that fragments of the block still remain on the top of Rattlesnake Mountain anticline, but if so they probably rest, Madison on Madison, and have not been detected. Along the divide between Rattlesnake valley, Pat O'Harra valley, and Dead Indian valley the trace of the fault plane could not be found, either because wholly removed by erosion or because Madison was faulted on Madison and not detected. In Sec. 3, T. 54 N., R. 104 W., the fault plane again emerges from beneath a small patch of Tertiary breccia and traces easily northwestward, to the point where the wagon road crosses Dead Indian Ridge, a distance

of four or five miles. Throughout this distance the Madison rests on the Red Beds. In Sec. 22, T. 55 N., R. 104 W., two prominent hills of Chugwater are capped with isolated patches of Madison.

In Sec. 16, T. 55 N., R. 104 W., the trace of the fault plane is lost, probably because it passes wholly into the Madison, where it is not easily detected. This view is supported by the fact that the Madison in this region appears to be excessively thick, as though repeated.

Not far from the center of T. 54 N., R. 102 W., occurs an isolated peak known as Hart Mountain. It consists of a cap of several hundred feet of Madison limestone, entirely surrounded by late Cretaceous and Tertiary sediments. It has been described[1] as due to a circular fault. Because this mass of Madison is entirely isolated in outcrop, it is not possible to demonstrate the continuity of the major thrust, just described, to this point. But the supposition hardly admits of doubt that Hart Mountain constitutes a portion of the large fault block so widely exposed to the west, especially in view of the similarity of stratigraphic units involved.

The extreme irregularity shown by the fault trace is largely due to erosion, in part to later deformation, since the fault plane dips at various but low angles at various points.

The north and south extent of the fault has been proved for over 25 miles in a straight line and for more than double that distance measured along the sinuosities of its course. Exclusive of the Hart Mountain outlier the easternmost and westernmost exposures are separated by a distance of 7 miles; including Hart Mountain, by about 16 miles. At the westernmost exposure the fault passes beneath the Tertiary andesites and is lost. At this point the Madison rests on the Fort Union (?), which in turn can be traced without break at least 6 miles farther west. If the movement was from the west eastward, as will be shown later, the fault plane must pass at least this far west, hidden below the lava, but cut through by erosion before the lava was poured out. If this is the case, the amount of displacement must have been not less than 22 miles, making no allowance for recession of the eastern front by erosion. Using average figures for the thickness of the beds involved, the vertical displacement is over 6,000 feet.

[1] C. A. Fisher, *loc. cit.*

There is nothing sufficiently regular about the dip of the fault plane to indicate the direction of movement. The fact, however, that the Cretaceous and Tertiary rocks in the Bighorn Basin to the east are continuous and but slightly disturbed for nearly 100 miles indicates plainly enough that the faulted block did not come from the east. The thick cap of volcanics to the west makes it impossible to expect any evidence in that direction, but in spite of that is seems clear enough that this block moved from west to east.

The South Fork thrust.—Along the lower valley of the South Fork of Shoshone River a second thrust fault is exposed on both sides of the valley, below the Hart Mountain thrust already described. As far as this fault could be traced, Sundance was found resting on Cody or Fort Union(?), and a section from the river level to the top of the ridge on the south side of the valley reveals the following situation:

Top
 Madison
 . . . . Major thrust
 Fort Union(?)
 Cody
 Frontier
 Thermopolis and Mowry
 Cloverly
 Morrison
 Sundance
 . . . . Minor thrust
 Cody
Bottom

On the north side the section is as follows:

Top
 Madison
 . . . . Major thrust
 Frontier
 Thermopolis and Mowry
 Cloverly
 Morrison
 Sundance
 . . . . Minor thrust
 Cody
Bottom

This fault seems to pass wholly into Cody shales both to the north and south and cannot be traced more than 6 or 8 miles. It probably shows again, in Sec. 11, T. 52 N., R. 104 W., on the north side of the North Fork, where abundant Sundance fossils are found on Cody shale slopes, just at the base of the main Madison scarp. It has a horizontal displacement approximating 10 miles, and a vertical movement of about 3,000 feet, or nearly 10,000 feet for the two faults combined.

Near the west line of T. 51 N., R. 103 W., the trace of this fault, which lies about S. 45 W., on both sides of the valley is suddenly lost in an area of intense brecciation, which is believed to mark the site of a transverse fault. The transverse fault seems to have shifted the trace of the thrust northwest about a mile, and west of the point of disturbance the thrust can be traced only on the south side of the valley. On the north side it is probably buried beneath Tertiary lavas. It has not been possible to prove the identity of the thrust planes east and west of the transverse area of disturbance, but the similarity of stratigraphic relationships [Sundance on Cody and Fort Union(?)] seems to indicate the possibility of the foregoing explanation.

The thrust plane appears to have been sharply folded along an axis lying about northeast and southwest, parallel to the trend of the South Fork Valley. At one point where a deep gorge cuts the axis of a sharply overturned anticline, not far south of Ishowooa Post-Office, yellow sandstones are exposed in a very small area beneath typical Sundance beds. The sandstones carry no fossils, but are similar in appearance to the Fort Union(?), and if of Fort Union(?) age the exposure represents a "Window" or "Fenster," such as has been described by several writers, in connection with major thrusts elsewhere.

Beartooth fault zone.—Along the eastern edge of the Beartooth Plateau, from the Clark Fork to the Montana line, is a zone of thrust faults, probably related to the same forces producing the faults already described though not continuous with them. The southern extremity of this zone lies about 8 miles north and 4 miles east of the northernmost point to which the Hart Mountain thrust was traced. This group of faults, all of which are associated with

overturned folds, in places carries the Pre-Cambrian granite out over the "Red Beds." The fault planes could not actually be observed, but are undoubtedly much steeper than the plane of the Hart Mountain thrust. The amount of horizontal displacement was not determined.

Mechanics of the faulting.—While no theoretical discussion of the mechanics of these great faults is proposed, it seems worth while to present some observations which may ultimately help to throw light on the problem:

1. The fault contact is practically everywhere concealed by talus from the Madison cliffs, but at several places it could be located within a few feet, and the zone of crush breccia is notably thin at most points.

2. The great limestone block above the fault plane is little folded. But while it presents the general aspect of a nearly flat-lying horizon, locally the dips are high, as a result of numerous small normal faults which appear to have been the result of the settling of the great block after the thrust ceased.

3. The soft shales below the major thrust plane, while much crumpled at places, are nearly horizontal and almost undisturbed over considerable areas where exposed by erosion several hundred feet lower than the major thrust.

HISTORY

The history of the faulting in this region depends, for its correct solution, on the careful determination of the age of the beds herein called Fort Union(?) and on a knowledge of the relation of these beds to the faulted block of Madison limestone. The second part of the problem is comparatively simple, and will be discussed first.

For long distances these beds occur at the foot of the Madison scarp, and there was little question from the very first that they passed beneath the Madison block. In view, however, of the statement of Hewett that these beds are probably of Wasatch age, it was thought possible that the sandstone might have been deposited, after the faulting and erosion, against the foot of the limestone scarp, since it was nowhere possible to find an actual contact of the Madison resting directly on the Fort Union(?).

If, however, the sandstones were laid down against the base of these high cliffs, they should contain a coarse and abundant angular limestone conglomerate, whereas a careful search nowhere revealed any Madison limestone in any of the sandstone of the formation. This constitutes abundant evidence that the Fort Union(?) actually passes beneath the fault block and does not lap against its foot.

As to the second problem, the exact age and equivalence of the beds called Fort Union(?), a less definite conclusion is possible. They are younger than the Cody, upon which they rest with slight angular unconformity at places. The fact that they are involved in the major faulting and folding makes it probable that they are not Wasatch, as Hewett has suggested, since beds of that age are known to cover similar major faults in Idaho.[1] The only other formations with which it seems at all possible to correlate them are Hewett's Gebo (Fisher's basal Laramie) or Hewett's Fort Union(?) (Fisher's upper Laramie), and to the writer the evidence seems in favor of the latter conclusion. If these beds are the equivalent of Hewett's Fort Union, it still remains to determine whether they represent the equivalent of the original Fort Union and whether they are very late Cretaceous or early Tertiary, problems with which this paper has nothing to do.

These faults involving the Fort Union(?) pass at many points beneath the Andesite, which Hague, in the Absaroka Folio, has called the Early Basic Breccia and which he considers to be of early Neocene age. This would date the faulting as taking place after the sedimentation of the Fort Union(?) and before the Neocene, probably in very early Tertiary time, since following the faulting long erosion had trenched the region deeply and in places completely cut away the fault block, before the Basic Breccia was laid down.

CORRELATION WITH OTHER FAULTS

Richards and Mansfield[2] have presented a concise statement of the available information regarding major thrusts in the northern Rocky Mountains, and hazard a possibility that these may consti-

[1] R. W. Richards and G. R. Mansfield, "The Bannock Overthrust," *Jour. Geol.*, XX (1912), 704.

[2] *Op. cit.*

tute parts of one major thrust, carved into isolated portions by erosion. As they suggest, however, such correlation awaits further and more careful study, particularly as to the dating of the faults. To the information they have gathered may be added the more recent work of Haynes[1] on the "Lombard Overthrust" in Montana.

The present paper is presented as a further contribution to the subject, and, while conclusions as to correlation are still premature, the writer believes it to be quite improbable that these various faults will ultimately be found to be a part of one great overthrust. It seems much more likely that they represent numerous "Decken" or rock sheets, the one driven over the edge of the next after the manner described by Geikie[2] in discussions of Alp ne structure. Two such rock sheets, one above the other, are exposed along the South Fork of Shoshone River, in the area here described.

[1] *Jour. Geol.*, XXIV (1916), 269.

[2] Geikie, *Mountains, Their Origin, Growth, and Decay.*

THE ORIGIN OF VEINLETS IN THE SILURIAN AND DEVONIAN STRATA OF CENTRAL NEW YORK[1]

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CONTENTS

INTRODUCTION

Although the origin of metalliferous veins has long been of interest to the geologist and mining engineer, very few facts have been definitely established concerning the mechanics of vein formation. Direct investigation of the subject is difficult because of the complexity of the processes involved and because only the final results are available for examination. The evidence that may have existed during the early stages of vein growth has commonly been obliterated by alterations due to vein-forming solutions or to secondary changes. Most metalliferous veins are found in regions of dynamic metamorphism and where igneous processes have been active. Consequently these veins, as a rule, furnish little or no evidence relative to the mechanics of their origin. The study of small barren veins in regions of unaltered sedimentary rocks has been largely neglected because they are of no commercial importance, and yet such veins often furnish more positive evidence con-

[1] Presented in abstract at the Albany meeting of the Geological Society of America, December, 1916.

cerning the mechanics of vein formation than is to be found in the larger and more complex ones. It was for this reason that the present investigation was undertaken.

Many small veins are present in the Silurian and Devonian formations of central New York. These rocks are well exposed in the numerous limestone and gypsum quarries of Cayuga and Onondaga counties. In the summer of 1916 the writer visited all of the quarries now being worked in these counties and nearly all of those that are idle, but most of the data used in this paper were obtained in the extensive quarries found in the vicinity of Union Springs.

STRATIGRAPHIC FEATURES

The rock formations outcropping in the region studied are listed below:

Devonian
- Skaneateles shale
- Cardiff shale
- Marcellus shale
- Onondaga limestone
- Oriskany sandstone and conglomerate

Silurian
- Manlius limestone
- Roundout limestone
- Cobleskill limestone
- Bertie waterlime
- Camillus shale
- (Syracuse salt)
- Vernon shale

(Bertie waterlime, Camillus shale, (Syracuse salt), Vernon shale: Salina formation)

Rock salt in the form of lens-shaped beds is present at many places immediately below the Camillus shale, but it has been removed in solution wherever the covering is less than about 1,000 feet thick, and therefore is never found near the outcrops of the strata.[1]

The Camillus shale contains intercalated beds of impure magnesian limestone and of gypsum. The limestone layers are more abundant in the upper part of the shale and probably represent

[1] D. H. Newland and Henry Leighton, "Gypsum Deposits of New York," *N.Y. State Museum Bull. 143*, 1910, p. 21.

transitional stages toward the Bertie waterlime. The gypsum is highly argillaceous and in places grades into gypsiferous shales. Partings of shale, ranging in thickness from a fraction of a centimeter up to several meters, are usually present, dividing the gypsum into several beds. These beds thin out and disappear, so that their number and thickness vary greatly in different districts. In many sections they are entirely absent. Gypsum may be found in small quantities all the way from the bottom to the top of the Camillus shale, but usually most of it is near the top.

The Onondaga limestone is commercially the most important of the limestone beds, and therefore there are many quarries located all along its outcrop; but the Cobleskill and Manlius limestones are also being quarried at several places. The lower layers of the Onondaga limestone, locally known as "gray limestone," have a well-developed crystalline texture similar to that of marble. The limestone forming the upper portion is bluish gray in color, dense, fine-grained, and contains numerous nodular concretions of chert or hornstone. Microscopic examination shows that the "blue limestone" consists essentially of irregular grains of calcite and small crystals of pyrite, while rhombic crystals of calcite may occasionally be distinguished.

The chert varies in color from light bluish gray to almost black, and on freshly fractured surfaces is often difficult to distinguish by color or texture from the inclosing limestone (see Fig. 6). It is irregularly distributed, occurring often in small isolated nodules, though more commonly the nodules are arranged in well-defined rows or layers, and in places these layers of disconnected nodules pass by gradation into more or less continuous and uniform layers or bedded veins, which may be 3 cm. or more in width and extend for distances of many meters. The chert masses have evidently been formed through replacement of the limestone, for some of them contain fossils in which the details of structure are perfectly preserved. On weathered surfaces the chert, because of greater resistance, stands out in sharp relief. Microscopically the chert is cryptocrystalline, and the boundary between limestone and chert is not sharply defined. In passing from limestone to chert there is a gradual though rapid decrease in calcite with a correspond-

ing increase in silica, but all of the chert examined contains numerous inclusions of calcite in the form of rhombohedral crystals (0.05 mm. and less in diameter), somewhat larger than the similar rhombs in the limestone.

STRUCTURAL FEATURES

The rock strata have been disturbed only slightly since their emergence from the sea. In general, the dip is toward the south at an average inclination of 7 to 10 m. per kilometer, but in a few places, because of gentle folding, there is locally considerable variation from this average.

Jointing is well developed throughout the area, and is probably due chiefly to the adjustment of strains resulting from folding and tilting. Appreciable openings are not found along these joints except near the surface, where, under favorable circumstances, they have been widened by the solvent action of descending surface water, and in such instances little or no deposition is to be observed on their walls. The fracturing of the rock strata seems to have resulted from compressive forces which would tend to prevent the formation of open fissures. The joints cut the veins of the region, and are therefore, in part at least, of later origin.

A thrust fault with displacement of a few centimeters is exposed in the Backus quarry, two miles north of Union Springs, and here the drag of the rock strata on both sides of the fault plane indicates that the displacement was accompanied by sufficient pressure to keep the fracture closed. A narrow vein of selenite follows this fault. Hopkins has described several thrust faults in the vicinity of Syracuse, the displacements ranging from a few centimeters to a little over a meter.[1]

Certain local disturbances of the rock strata, not noticeable in the overlying formations, may be observed in the Cobleskill limestone and the upper beds of the Salina. In places these strata have been pushed upward in such a way as to form low domelike elevations on which the joints sometimes have a radial arrangement. A group of six or more domes may be found a kilometer southeast

[1] T. C. Hopkins, "The Geology of the Syracuse Quadrangle," *N.Y. State Museum Bull. 171*, 1914, p. 29.

of Aurelius Station. They are strung out in a general north and south line near the bottom of a hill slope, and at the foot of the hill, close to the base of the domes, there are several large springs with deposits of calcareous tufa below them. A small quarry has been opened in one of the larger domes, which has a diameter of about 50 m. and height of 4 m.

Hartnagel[1] thinks that these domes are due to an increase in volume of the underlying beds, because of the formation of gypsum from anhydrite; but the present writer has found no evidence supporting this view. The shape of the domes, their location, and their general associations are such as to suggest that they have been formed in the same way as the salt and gypsum domes of Louisiana and elsewhere, which have been described and explained by Harris.[2] No open fissures, except where joints had been widened at the surface by weathering, and no veins were observed in any of the domes.

Open spaces of appreciable size are infrequent except in the upper beds of the Salina. The Bertie waterlime contains numerous small cavities attributed by Vanuxem to the solution of salt, since they sometimes exhibit the hopper-shaped outlines of halite crystals. The intercalated layers of magnesian limestone in the Camillus shale usually show the same porous structure and hopper-shaped casts. These cavities are frequently lined with a calcareous deposit. Small cavities, caused by the partial solution of fossils, are occasionally found in some of the limestones, and these openings are often lined with calcite, chalcedony, or crystals of quartz.

Open fissures of mechanical origin were found in only one locality, in Camillus shale exposed by a cut on the Lehigh Valley Railroad about 100 miles west of Cayuga Junction. The cracks are 1 cm. or more in width, and are partly filled with a calcareous deposit having the appearance of finely banded travertine or onyx marble, the layers of which are tinted various shades of light yellow and reddish brown. The material is similar in every way to the deposits lining cavities in the Bertie waterlime and to layers in

[1] C. A. Hartnagel, "Preliminary Observations on the Cobleskill ('Coralline') Limestone of New York," *N.Y. State Museum Bull. 69*, 1903, p. 1135.

[2] G. D. Harris, "The Geological Occurrence of Rock Salt in Louisiana and East Texas," *Econ. Geol.*, IV (1909), 12–34.

some of the calcareous tufa now forming in places on the surface. These fissures are possibly due to the solution and removal of underlying salt beds or perhaps to other superficial disturbances, since the deposits were evidently formed in the belt of weathering.

TYPES OF VEINS

Structurally the veins are of two different types: one fibrous, the other more or less coarsely crystalline and non-fibrous. The former are composed either of gypsum or calcite, the crystal fibers extending transverse to the strike of the veins, which run in all directions, but are generally parallel to the bedding. These veins are lenticular and continue for short distances only. The non-fibrous veins usually consist of gypsum or calcite, but the calcite veins sometimes contain accessory quartz and pyrite. They are more persistent and more uniform in width than the fibrous veins, and most of them are vertical or steeply inclined. The evidence indicates that each type had a different mode of formation.

SOURCE OF THE VEIN MINERALS

In the veins under consideration there can be no question as to the source of the vein minerals, for it is evident that they have been derived from the neighboring rocks. The veinlets found in the gypsum-bearing strata of the Salina are composed of gypsum, while those occurring in the limestones, waterlimes, and calcareous shales consist essentially of calcite. It is not the purpose of the writer, however, to imply that the vein minerals found in other and larger veins have usually had a similar source.

DESCRIPTION OF THE FIBROUS VEINS

The fibrous (satin spar) veins are larger and more abundant in the gypsum-bearing strata, probably because of the greater solubility of gypsum as compared with calcite. As a rule they are less than 3 cm. in width and from 20 to 50 cm. in length, but in places they have a width of over 10 cm. and extend for distances of many meters. Most of the veins are highly lenticular in form; where a vein thins out it may be replaced by another a little to one side, so that the ends overlap. Veins frequently split into two or

more branches, but the intersection of veins is extremely rare. When numerous they are commonly grouped to form linked-vein systems, as in Fig. 1. The vein fibers are usually normal to the inclosing walls, occasionally they are oblique, and very rarely they are curved or abruptly bent. In some veins most of the fibers apparently extend from wall to wall without a break, while in others there is a well-defined central parting frequently marked by the presence of inclusions of the wall rock. Small vugs are found in a

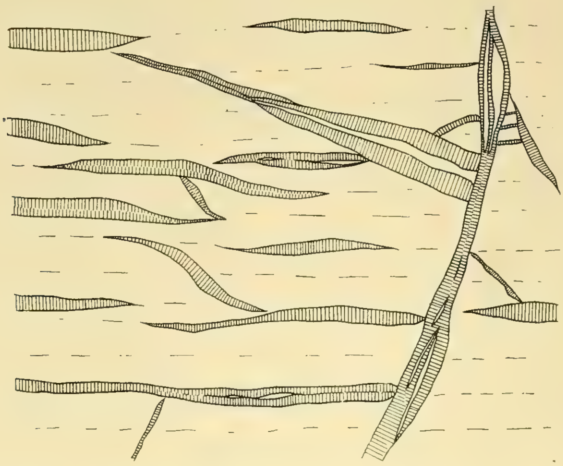

Fig. 1.—Veins of fibrous gypsum exposed in walls of quarry near Union Springs New York.

few veins, and these are lined with gypsum crystals of normal habit.

The veins of fibrous calcite are similar to those of fibrous gypsum except that ordinarily they are smaller and not so numerous. In both gypsum and calcite veins the fibrous structure is as highly developed in the larger veins as in those that are smaller, the diameter of the fibers apparently being independent of the size of the veins. However, the diameter of the crystal fibers does vary markedly with any change in the texture of the wall rock. In the fine-grained limestones and shales the fibers commonly have a diameter of 0.05 mm. and less, while in the Onondaga "gray limestone," with its coarsely crystalline texture, the diameters are as

great as 2 mm., and the fibrous structure is hardly noticeable in the narrower veins. Where veins of fibrous calcite in the Onondaga "blue limestone" pass through chert nodules, there is a sharp change in texture, the veins becoming coarsely crystalline and non-fibrous within the chert. This sudden change in texture is easily noticeable in veins that are less than a millimeter in width, when they are examined in thin sections under the microscope.

Where the veins are non-fibrous, the individual crystals usually have their longer dimensional axes parallel rather than transverse to the strike of the veins; and, especially in the smaller veins, most of the crystals extend from wall to wall. In the larger veins these crystals have maximum diameters of over 5 cm., while in the fibrous portion of the same veins the fiber crystals are uniformly 0.1 mm. or less in diameter. The larger crystals of calcite frequently show warped cleavages, and under the microscope undulatory extinction is common in these crystals and also in those of fibrous form. The fibrous crystals are very irregular in cross-section, since the prisms are not bounded by plane surfaces as is often true of the crystals found in the non-fibrous portions of the veins.

Vugs lined with calcite crystals of normal habit (simple rhombohedrons with some scalenohedrons) are occasionally present in the fibrous portion of the veins where the walls are of limestone, but they are more abundant where the veins are coarsely crystalline and have chert walls. The walls of the veins are sharply defined, and inclusions of the wall rock, limestone as well as chert, are common. When one wall of a vein contains angles or other irregularities, there are corresponding irregularities in the opposite wall, such that the two surfaces would fit closely together if placed in contact.

ORIGIN OF THE FIBROUS VEINS

In previous papers[1] the writer has cited evidence tending to prove that cross-fiber veins of the asbestiform minerals could not have been formed through any process of replacement or of recrystallization *in situ* and that they were not deposited in open fissures.

[1] Stephen Taber, "The Origin of Veins of the Asbestiform Minerals," *Proc. Nat. Acad. Sci.*, II (1916), 659–64; and "The Genesis of Asbestos and Asbestiform Minerals," *Bull. Am. Inst. Min. Eng. No. 119*, 1916, pp. 1973–98.

Most of the objections raised against these theories of vein formation are equally applicable in the case of the veins of fibrous calcite and gypsum; and, in the descriptions given above, much confirmatory evidence may be found. All of the structural features characteristic of these veins have been duplicated in fibrous veins grown in the laboratory where their origin and growth could be observed in detail.[1] In view of all the facts obtained from field investigations and laboratory experiments, the conclusion is inevitable that the veins of fibrous calcite and gypsum have been formed through a process of lateral secretion, the growing veins making room for themselves by pushing apart the inclosing walls, and that the fibrous structure is due to the circumstance that the material for crystal growth was accessible in only one direction.

Calcite and gypsum are not normally fibrous, and wherever they have developed this structure it is due to the physical conditions which have prevented crystal growth, except in one direction. Merrill has described fibrous incrustations of gypsum forming on the walls of caves, and notes that the growing crystals not infrequently force off pieces of the limestone of considerable size.[2]

Laboratory experiments and field investigations indicate that the essential conditions for the growth of fibrous minerals, such as calcite and gypsum, are: (1) the growing crystals must be in contact at their base with a supersaturated solution; and (2) the solution must be supplied through closely spaced capillary or subcapillary openings in the surface of the wall rock. In the fine-grained limestones and shales the constituent particles are relatively small, and therefore the open spaces which are chiefly subcapillary in size are closely spaced; but in the crystalline "gray limestone" with its coarser texture these openings while no larger are necessarily more widely spaced. This explains the coarse texture of the fibrous veins occurring in the "gray limestone." The coarsely crystalline non-fibrous structure of veins where they pass through chert masses is due to the relative impermeability of the chert which has here

[1] Taber, "The Origin of Veins of the Asbestiform Minerals," *Proc. Nat. Acad. Sci.*, II (1916), 659–64; and "The Genesis of Asbestos and Asbestiform Minerals," *Bull. Am. Inst. Min. Eng. No. 119*, 1916, pp. 1973–98.

[2] G. P. Merrill, "On the Formation of Stalactites and Gypsum Incrustations in Caves," *Proc. U.S. Nat. Mus.*, XVII (1894), 81.

prevented the addition of new material directly through the walls, thus forcing it to reach the growing crystals by diffusing between the walls. Vugs result from a deficiency of material necessary for growth because of insufficient concentration or because of relative inaccessibility. The latter probably explains the greater abundance of vugs between chert walls.

DESCRIPTION OF THE NON-FIBROUS VEINS

The non-fibrous veins range up to 5 cm. or more in width and in some instances are exposed for distances of 15 or 20 m. along the strike. Where they pinch out and disappear, they are sometimes replaced by others a few centimeters to one side or farther along the line of strike. Such vein systems may be traced for over 50 m. The veins show no appreciable change in appearance where they pass from one rock to another of different texture or composition. A vein exposed in the limestone quarry near Farleys can be traced upward through the argillaceous Manlius limestone, 20 cm. of Oriskany conglomerate, and into the Onondaga limestone, yet at no place is any variation in its appearance perceptible.

The vein walls are sharply defined, and fracture usually takes place more readily along the contact between vein and wall rock than in other directions. The opposite walls of a vein are parallel even when they are very irregular, and they would therefore fit intimately together if placed in contact (see Fig. 2). Angular fragments of the wall rock are occasionally present in the veins; and in many instances, by making parallel sections, it is possible to prove that they are in contact neither with other fragments nor with the walls. Most of the fragments show no evidence of rotation although they have been displaced through distances of 2 cm. or more (see Fig. 3). In places a fragment adhering to both walls of a vein appears to have been separated into several fragments by continued vein growth, as in Fig. 4.

Some veins have a banded structure with coarsely crystalline non-fibrous calcite in the center and a band of fibrous calcite along each wall. This is probably due to two stages of vein growth, as is indicated by the veins sketched in Fig. 2. Other veins are roughly banded, with pyrite along the walls and calcite in the center (see

Fig. 5), but in such cases the pyrite was deposited subsequent to the deposition of most of the calcite, and well-formed cubes and pyritohedrons may be found replacing impartially vein calcite and wall rock. Small seams of pyrite in places cut directly across the veins.

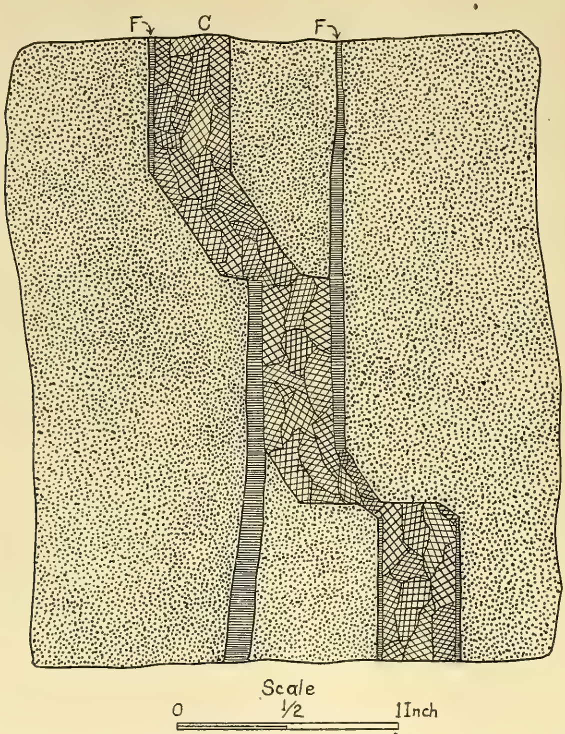

FIG. 2.—Calcite veins in limestone. Coarsely crystalline calcite (C) and fibrous calcite (F).

ORIGIN OF THE NON-FIBROUS VEINS

The facts cited above preclude the theory that these veins are due to recrystallization of country rock *in situ* or that they could have been formed through replacement; and the presence of detached inclusions of wall rock argues against the hypothesis that the veins were deposited in open fissures. If the veins were formed as a result of fissure filling, deposition of vein matter must have begun on the walls and continued inward until the opposite sides

met, thus forming a suture line near the center, but there is no evidence that such a suture was ever present in any of the veins under consideration. Large calcité crystals commonly extend without interruption from wall to wall, and in one vein a well-formed crystal of quartz, with a pyramid at each end of the prism,

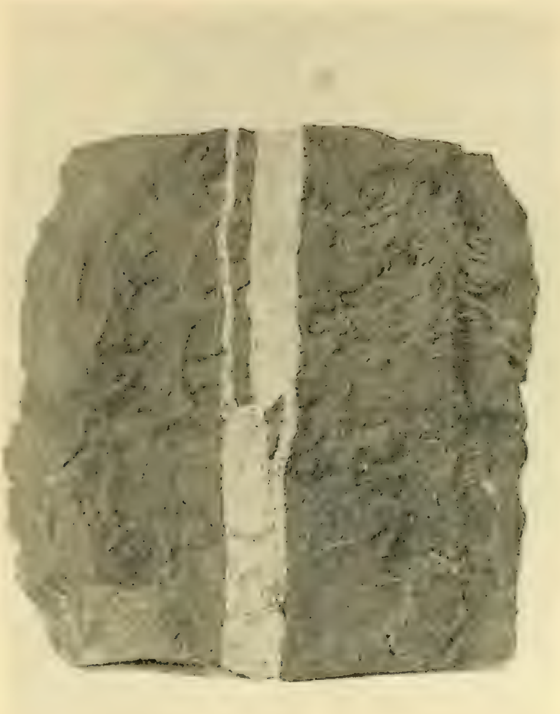

FIG. 3.—Calcite vein in limestone showing angular inclusion of the wall rock. Two-thirds natural size.

was found extending across almost the entire width of the vein (see Fig. 5).

The best evidence bearing on the origin of the veins is, perhaps, furnished by certain chert nodules containing veinlets of calcite, ranging up to 2 or 3 mm. in width, which do not extend into the inclosing limestone (see Fig. 6). The force separating the chert walls was applied so gradually that any stresses set up in the

limestone were adjusted by recrystallization, in the same way that slabs of marble or limestone may be slowly deformed under forces acting through a long period of time. This process probably also explains the curving walls of the lenticular veins.

The facts here listed are difficult or impossible of explanation under any of the hitherto generally accepted theories of vein formation. They are, however, easily explained on the hypothesis that

FIG. 4.—Calcite veins in limestone showing inclusions of the wall rock. Two-thirds natural size.

the vein-forming solutions entered along fractures, bedding planes, or other planes of weakness, where the openings were chiefly capillary or subcapillary in size; and that the separation of the vein minerals from solution was accompanied by the development of a force sufficient in magnitude to push apart the walls, and thus gradually make room for the growing veins. Circulation of solution through such narrow openings must necessarily be extremely slow, and under these conditions diffusion through the solution becomes an important factor in supplying additional material to the growing crystals.

Where veins pass through chert masses, most of the calcite crystals extend from wall to wall, and are oriented with their longer dimensional axes parallel rather than transverse to the vein walls—a fact that is likewise true of many non-fibrous veins in limestone and shale. Since this may be observed in the largest as well as the smallest veins, it means that the average number of vein crystals

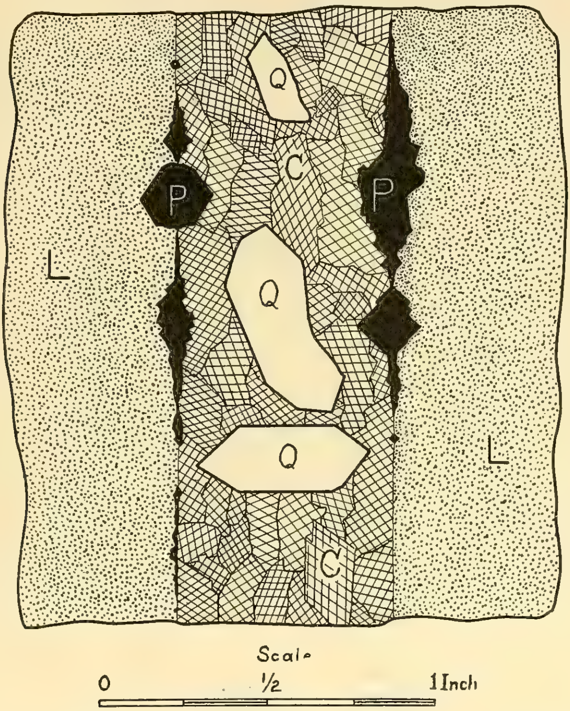

FIG. 5.—Vein consisting of calcite (*C*), pyrite (*P*), and quartz (*Q*), with walls of limestone (*L*). The pyrite replaces both the limestone and the vein calcite.

in contact with unit area of the wall tends to decrease with the growth of the vein. In other words, it is believed that with continued growth those crystals having any advantage, because of greater size, or more favorable orientation or location, tend to increase in size partly at the expense of their less fortunate neighbors. This conclusion is supported by the manner in which the inclusions have been displaced in some of the veins. The

enlargement of certain crystals at the expense of others does not, however, continue indefinitely.

NATURE OF FORCES THAT SEPARATED THE VEIN WALLS

It has been demonstrated that under suitable conditions crystal growth is accompanied by the development of a force which may even exceed the crushing strength of the crystals. The nature of

FIG. 6.—Chert nodule containing calcite veinlets which do not pass into the inclosing limestone. Two-thirds natural size.

this force has been discussed in several recent papers. Bruhns and Mecklenburg ascribe the pressure effects accompanying crystal growth to the "forces of adsorption and capillarity."[1] This has been refuted by Becker and Day and independently by the present writer. Becker and Day published a paper "with the purpose of demonstrating . . . . the existence of a linear force, apart from the volume expansion, exerted by growing crystals." They conclude (1) that

[1] W. Bruhns and Werner Mecklenburg, "Über die sogenannte 'Kristallisationskraft,'" *Jahresbericht der Niedersächsischen geologischen Vereins zu Hanover*, VI (1913), 106–8.

this force enables a crystal to grow in directions in which growth is opposed by external force "notwithstanding unrestricted opportunity for growth in other directions; (2) that the linear force thus exerted is of the order of magnitude of the breaking strength of the crystal."[1] Most of the phenomena that have been cited in support of the latter hypothesis may be explained, however, by the fact that the growing crystals have been in contact with a supersaturated solution in only one direction, or that the concentration of the solution has been greater in one direction than in others. The present writer believes that the pressure effects accompanying crystal growth are to be attributed chiefly to the molecular forces associated with the separation of solids from solution, and that the tendency to develop crystal faces is of minor importance.[2] Argument in support of this hypothesis has been given elsewhere.[3]

According to the writer's concept, the pressure developed during crystal growth is due, in most cases, to the fact that the solid can diffuse through a solution occupying small capillary or subcapillary spaces, while the crystalline mass built up by the separation of the solid from solution cannot escape through the small openings in like manner, even when under great pressure. The force observed during the separation of crystals from solution is believed to be analogous to the pressure developed when an anhydrous salt, confined in a limited space, combines with water that has diffused as vapor through capillary openings.[4] The diffusion of the solid through the solution is ascribed to osmotic pressure, and its separation therefrom to the relation between osmotic pressure and solution pressure.

Crystals grow through the addition of layers of material to their outer surfaces, and this can take place only when the surfaces are in contact with a layer of supersaturated solution, the concentration

[1] G. F. Becker and A. L. Day, "Note on the Linear Force of Growing Crystals," *Jour. Geol.*, XXIV (1916), 313.

[2] Stephen Taber, "The Growth of Crystals under External Pressure," *Am. Jour. Sci.*, Series 4, XLI (1916), 553–54.

[3] Stephen Taber, "Pressure Phenomena Accompanying the Growth of Crystals," *Proc. Nat. Acad. Sci.*, III (1917), 297–302.

[4] Stephen Taber, "The Genesis of Asbestos and Asbestiform Minerals," *Bull. Am. Inst. Min. Eng. No. 119*, 1916, pp. 1986–87.

of which is maintained by diffusion from without. When a crystal grows in a direction in which growth is opposed by external pressure, the pressure is transmitted through a thin layer of solution separating the crystal from the foreign body. The effect of pressure and of capillarity, if the latter be present, is to reduce the thickness of this layer to a minimum; but it would be difficult, if not impossible, to completely expel it by pressure alone from between two smooth parallel surfaces. And crystal growth would tend to make the surfaces under pressure parallel, for deposition would be most rapid where diffusion is least restricted, i.e., where the layer of solution is thickest. Therefore a crystal growing in a limited space may make room for itself by forcibly enlarging this space, if it is supplied with the material for growth by diffusion through solutions occupying spaces that are sufficiently small.

The solubility of most substances, including calcite, is increased by pressure, and when such a substance separates from solution, there is an increase in volume which may result in pressures greatly exceeding the crushing strength of the crystals, provided the solution cannot readily escape. If the material that incloses a growing crystal is rendered more soluble by pressure, it may be gradually removed in solution as the crystals are enlarged. This probably explains the replacement of limestone and vein calcite by the idiomorphic crystals of pyrite.

The tendency of a crystal to assume a regular polyhedral form is important as a factor in the development of pressure during crystal growth only in so far as it affects the relative solubility of the crystal in different directions. While the difference in the pressure that may be developed in any two directions during the growth of a crystal is probably small, it can accomplish appreciable results if continued through a long enough period of time.

SUMMARY AND CONCLUSIONS

The small and relatively simple veins of a region of unaltered sedimentary rock were studied in order to obtain field evidence bearing on the mechanics of vein formation. Two types of veins are described, one fibrous and the other coarsely crystalline and non-fibrous. Both consist essentially of calcite or of gypsum.

According to the author's theory, the fibrous veins owe their peculiar structure to the fact that the material for growth was supplied only to the base of the growing crystals through solutions occupying closely spaced capillary or subcapillary openings in the walls, while the non-fibrous veins were deposited from solutions that entered between the walls of narrow capillary fractures and bedding planes. Because of the slow rate of circulation through such minute spaces, diffusion through the solution is probably an important factor in supplying material to the growing veins.

The diameter of the calcite and gypsum fibers varies with the spacing of the openings through which the material for their growth is supplied, and is independent of the size of the veins. There is evidence of some recrystallization within the non-fibrous veins during the process of growth, as a result of which those crystals that for any reason are less stable than their neighbors are redissolved, thus furnishing additional material for the growth of others.

The field evidence, confirmed by laboratory experiments, indicates that the veins were not deposited in pre-existing openings, but that the growing veins have made room for themselves by pushing apart the inclosing walls. The presence of drusy cavities, banding, or crustification are not in themselves proof that a vein was deposited in a pre-existing open fissure.

The force that enables a growing vein to make room for itself is attributed chiefly to the molecular forces associated with the separation of solids from solution.

TRANSPORTATION OF DÉBRIS BY ICEBERGS

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Introduction.—On the east valley side of the southern end of the Cayuga Lake Valley, just to the north of Ithaca, New York, occur considerable areas of lake-clay deposits laid down when the waters of the lake were ponded to higher levels by the ice barrier of the retreating front of the last advance of the continental ice sheet. These lake-clay deposits are especially well developed in the zones marginal to the outer fronts of the higher-level deltas of streams tributary to the Cayuga Valley, and undoubtedly represent, in such cases, the extension of the bottom-set beds of the delta accumulations. The particular occurrence to which reference is made in this article is found at a level of 840 feet to the south and west of the top of a notable delta deposit of Fall Creek, having an average elevation of 930 feet (the block diagram, Fig. 1, illustrates the geography of the occurrence). Thus the clay may be assumed to have been laid down in water having a depth of 90 feet and removed from the nearest point of the steep front of the delta deposit by a little less than one-fourth mile. At the time when the delta and clay deposits were made the ice barrier must still have existed within the confines of the Cayuga Lake Valley, for the level of the delta top indicates that its building must have been coincident with the outflow of the lake waters across the north-south divide between Cayuga and Seneca Lake valleys, and the overflow of their combined waters was at a present elevation of 900 feet from the south end of the Seneca Lake Valley into the Chemung River and thus into the Susquehanna. On the other hand, it is unlikely that the ice barrier was immediately adjacent to the delta and lake-clay deposits, for the nearest point of the north-south divide with a low enough elevation to permit of a flow of water from the one lake valley to the other is found approximately 15 miles to the north

of their occurrence. To the south the divide is at every point much higher than 900 feet. Unless, therefore, the ice front is conceived as a long projecting point occupying the center of the lake valley and margined by lake waters on both sides for a considerable distance, the ice barrier should be placed comparatively remote from the site of the clay deposit. This concept is also in accord with observation of tidal and marginal-lake ice fronts in Alaska—there is an almost straight line truncation of the ice where it is fronted

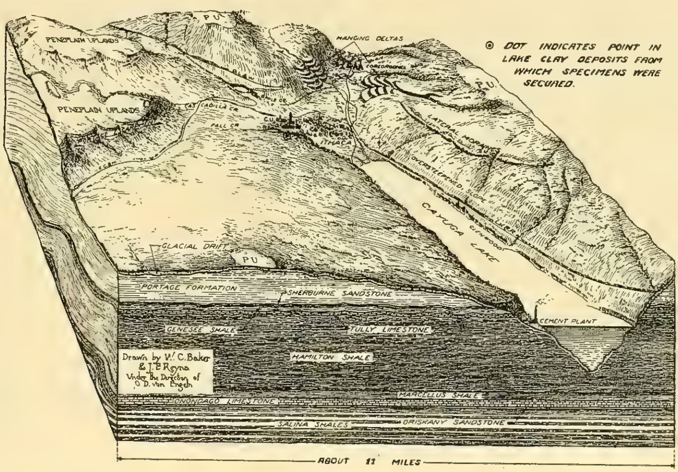

FIG. 1.—Block diagram of the region around the southern end of Cayuga Lake, New York.

by deep water. Again, the lake clay at the occurrence described has a thickness of at least 10 feet, and perhaps double that, with perfect, undisturbed stratification indicating a relatively long-continued period of deposition unaffected by minor oscillations of the ice front.

Purpose of paper.—It is the purpose of this paper to recount the recovery of rock material from a limited area and depth of this lake clay, to indicate the amount and character of this material, to account for its presence, and to make certain deductions from these facts with regard to the character and effectiveness of the erosive activities of glacial ice.

Recovery and nature of material.—In the course of gardening operations a trench approximately 25 feet long, 4 feet wide, and 3 feet deep was made in the lake clay. The clay deposit continued right up to the surface and was undisturbed and unmodified except for the top 12 or 16 inches that had been rendered more friable and amorphous in structure by plant growth and tillage. Below that the clay was exceedingly compact, fine grained, and slightly jointed with one-half- to one-inch spacing. From this clay, below the soil

FIG. 2.—Iceberg-dropped bowlders recovered from lake-clay deposit. Smaller pile apparently from single berg. Those marked *A* are striated or soled. Left to right diameter of bowlder at top of small pile is three inches.

layer, were dug the bowlders illustrated in Fig. 2. For the most part these were found in clusters of from three to five or more specimens occurring near each other. The bowlders in the smaller pile in Fig. 2 were all clustered within some 3 cubic feet of the clay at about the same depth. The total weight of all the bowlders is 74.5 pounds, of those in the smaller pile 8.5 pounds. In addition there were no doubt other rather large-sized bowlders that were overlooked, as no effort was made to go over the material with extreme care; and many observed smaller pebbles were not preserved. In any event the actual mass of the material present within the space excavated has no special significance; the figures are quoted merely to give some idea of the quantity of such bowlder

inclusions within the particular section of the clay that was examined. Possibly adjacent areas might have much greater masses, but the probability (as indicated by inspection of other near-by excavations) is that the average number would be lower, though occasional very large bowlders might make the mass as great, or greater, per average cubic foot of clay. It should be noted that away from the spots where the clustered bowlders occurred the clay was almost absolutely free from sand or grit.

Two distinctive charactersitics are immediately apparent on inspection of the material: (1) Many of the specimens (26 per cent of their number) show signs of glacial grinding, have striations, are "soled," or rudely faceted. In Fig. 2 a number of these are indicated by the letter *A*. (2) Much of the material (55 per cent by number, 67 per cent by weight) is from quite distant outcrops, that is, of rock material not available at the surface for a distance of 50 miles or more to the north even if the bottom of the lake is taken into consideration. Twenty-two of the 125 bowlders come from so distant a source as the Adirondacks or perhaps from Canada. There are 3 granites, 1 syenite, 12 gneissic, and 6 schistose specimens irrespective of size. Very prominent in the foreign material are Medina sandstones and Potsdam sandstones and conglomerates; of these three varieties there are 46 specimens. With one exception the large fragments, in general, are of the more resistant rock kinds from distant sources. The exception is a notably large piece of local sandstone derivable from bedrock outcrops extending from the area of the clay deposit to 10 or more miles to the north. This large local specimen is very conspicuously ground off on one side.

Source of the bowlders.—The only feasible explanation of the occurrence of these large rock fragments interbedded with the fine clay is that they are iceberg droppings. Icebergs, calved from the relatively distant glacier front, floated over the areas on which the clay was depositing and, on sufficient melting, dropped their rock load into the fine clay sediment, later deposits of which buried them completely. The bergs do not seem to have been grounded, for there is no apparent disturbance of the clay layering, though the clay material is so fine that in its oozy, under-water condition it

may have been too fluid to register so temporary a disturbance as the rocking and melting of a stranded berg.

Almost similar conditions of deposit of débris by icebergs have been observed on a tidal flat adjacent to the end of the Columbia Glacier, Alaska. There, at low tide, were exposed wide areas of fine-grained clay deposits. All over the surface of these clay deposits were scattered "nests" of glacial bowlders deposited by icebergs (calved from the adjacent Columbia Glacier) that had floated over the area at high tide (Fig. 3). The streaks on the mud

FIG. 3.—Bowlders dropped by icebergs on tidal mud flat adjacent to front of Columbia Glacier, Alaska. Streaks are due to the dragging of the bottoms of bergs floating in and out with the flow and ebb of the tide.

are occasioned by the dragging of partly floating bergs with the ebb of the tide. Similar "nests" of iceberg-deposited bowlders were a common feature on the sand beaches of the west side of Yakutat Bay, Alaska (Fig. 4). Here the pits in which the bowlders are nested are conspicuous because successive tides rocked the stranded bergs (Fig. 5) back and forth sufficiently to make quite an excavation before the ice melted completely.

Significance of observations.—From the foregoing observations of deposits adjacent to Pleistocene ice fronts and near living glaciers it is apparent that icebergs can and do carry notable quantities of

rocky débris and may deposit this at considerable distances from the calving end of the glacier. The fact that so large a percentage of the bowlders found in the clay deposit showed evidence of wear indicates that the material was largely derived from the bottom ice of the glacier. In fact, in collecting specimens of glacially striated pebbles, it is the common practice in this locality to resort to a deposit of glacial-lake clay for the material, as a large proportion of the bowlders found in such deposits exhibited these markings remarkably well preserved. Assuming that each of the bowlder

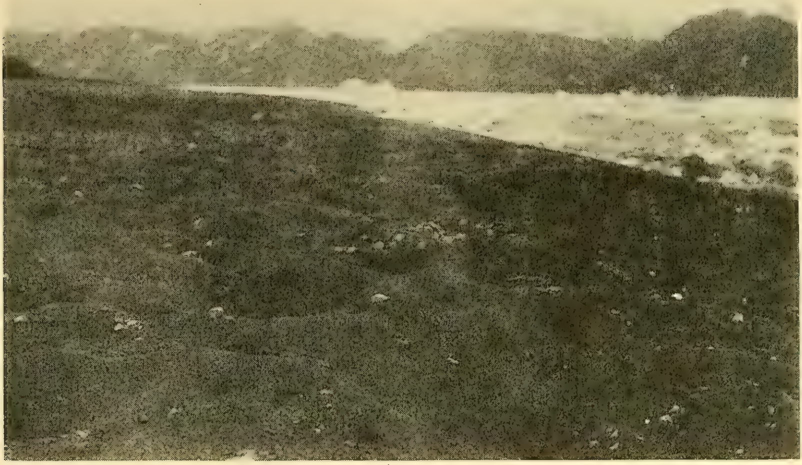

FIG. 4.—"Nests" due to rocking of stranded icebergs. Pebbles and bowlders on the surface of the sand and in the pits were included in the ice and deposited on its partial or complete melting. West side of Yakutat Bay, Alaska.

"pockets" in the clay is the result of the melting down of a single berg (and this seems very clearly to have been true of the material included in the smaller pile of Fig. 2 at least), it follows that the bottom ice must have been quite thickly shod with rock fragments. In other words, the material in transport at the bottom of the ice in any one cross-section must have been of considerable mass, and this material could have been acquired only by actual ice erosion of the bedrock over which it passed. Such being the case, the striking absence of local rock material in these iceberg deposits acquires a particular significance. It would appear that the local

rock material, being of comparatively slight resistance to grinding (mostly shales and thin bedded sandstones, commonly argillaceous), is reduced to rock flour almost immediately, while the resistant quartzitic and igneous material from distant sources survives. An alternative interpretation is that the local material of little resistant nature is not much subject to plucking, is eroded only by grinding, hence yields few sizable fragments. The same conclusion is suggested by the fact that the large-sized surface and near-surface erratics of local origin in the glacial deposits of the area about

FIG. 5.—Stranded icebergs, showing some with included débris. West side of Yakutat Bay, Alaska.

Ithaca, New York, are in very high percentage fragments of the Tully limestone, which outcrops in relatively massive layers, 2 to 10 feet thick, about 4 miles to the north of Ithaca and at other points more remote. It is also of interest to note that these large Tully erratics are in almost every case very conspicuously smoothed by ice wear and have usually the appearance of having lost a considerable part of their mass by such grinding, though it is of course commonly rather difficult to estimate how large the plucked block was originally. That the single large, local sandstone fragment found in the clay deposit was also very notably ground off is evi-

dence of the same kind. Specifically the fact that both the Tully limestone erratics and the local sandstone fragment in the iceberg deposit show conspicuous wear indicates that in the short distance such fragments traveled, and presumably under the thin, waning front of the glacier, there was nevertheless accomplished a very notable amount of erosion of these fragments, and it may be inferred that the bedrock surface over which the fragments were dragged was subjected to a like amount of reduction. This suggests that even the relatively thin and inactive frontal lobes of waning glaciers are quite effective erosive agents.

Summary.—Iceberg deposits of bowlders, found in fine-grained lake clay, occur in pockets, as if derived from single bergs. If that is the case the material brought by each berg is of considerable mass. The bowlders are in very high percentage of foreign, resistant rocks, and a very large proportion of the specimens shows signs of mechanical wear of glacial nature. Hence it is concluded that the iceberg deposits examined were from the bottom ice of the glacier. Locally derived material found in the deposits shows similar wear. Since these iceberg deposits must have been the very last deposits made by the last retreat of the ice, it is argued that the notable grinding of the local material indicates that even the thinned lobes of a waning glacier had considerable erosive effectiveness.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Leith, C. K. and Mead, W. J. *Metamorphic Geology.* Henry Holt & Co., New York, 1915. Pp. xxiv+337, figs. 35, pls. 16.

This is one of the most valuable of recent petrologic textbooks. The experience of the authors in the interpretation of metamorphic processes would make this work of great value even though there were many books on the subject; since this is actually the only general textbook, it is doubly valuable and welcome.

Under the term rock-metamorphism the authors include not only the changes involved in the formation of rocks commonly called metamorphic, but also all mineralogical, chemical, and physical changes which have taken place in rocks subsequent to their primary crystallization from the magma, thus including in the definition cementation and rock-weathering. In other words, the metamorphic processes here included are both the destructive processes of katamorphism and the reconstructive processes of anamorphism, together forming the metamorphic cycle.

The writers take up first the katamorphism of acid igneous rocks, katamorphism being used "to cover all alterations of a disintegrating or decomposing nature, whether accomplished by weathering or by thermal solutions, whether at the surface or below." The most important phase of katamorphism is weathering, or the alteration of surface rocks by the agencies of the atmosphere and hydrosphere. By this process the rocks decompose and disintegrate, and part of the constituents are carried away in solution, while the residue forms a porous mass which in many cases retains the texture of the original rock. Clay, sand, carbonate, and salt in aqueous solution are the end-products of katamorphism. Chemically the changes are chiefly hydration, carbonation, oxidation, and desilication; mineralogically there is a destruction of some minerals and a simplification of others, the minerals in many cases passing through intermediate forms before reaching the simple end-products. Another change produced is one of volume, there being an increase by the formation of pore space, by the addition of water,

carbon dioxide, and oxygen, and by the decrease in the average specific gravity of the minerals formed.

The authors do not lay much stress upon the zones of katamorphism and anamorphism, emphasized by Van Hise, for the zone through which katamorphism extends, for example, has very indefinite limits, both katamorphic and anamorphic changes being possible simultaneously at moderate depths in different kinds of rocks, or in the same kind of rock under different conditions.

The weathering of granite is used as a type of katamorphism. The rock used as an example is a Georgia "granite," and although so called by Watson it is not a granite, neither mineralogically as shown by the table on page 6, nor chemically. It is a quartz-monzonite verging toward a granodiorite, and not greatly different from Lindgren's type granodiorite. So far as the results of the alteration go, however, it is immaterial what the rock is called, and the term granite may be used in the "commercial sense." In this chapter 16 pairs of analyses, representing the weathering of acid igneous rocks, are shown by "straight-line diagrams," which well illustrate the changes which have taken place.

The second chapter treats of the katamorphism of basic igneous rocks, 17 pairs of analyses being given in the second plate.

In the third chapter the production of bauxite and laterite by the extreme weathering of rocks is discussed, the authors maintaining that bauxite and the associated clays are the products of the surface weathering of syenite by normal processes of rock-decomposition, and that they are not chemical sediments. They believe that kaolin is an intermediate stage and that they can trace the gradation from syenite through kaolinized syenite to bauxite wherever fresh cross-sections appear. There is a good discussion of the formation of laterite and associated iron ores in Cuba.

A comparison of the two plates showing the hydrothermal katamorphism of 29 igneous rocks with the plates showing normal weathering gives a clear conception of the differences between these two types of alteration.

So far the book has dealt with the katamorphic destruction of igneous rocks and with the nature and distribution of the end-products. The katamorphism of sediments, ores, etc., is now taken up in several chapters, and is followed by 30 pages on the redistribution of the constituents of the average crystalline and igneous rocks during katamorphism. Here the redistribution of the constituents is considered in terms of sediments—first in weight proportions of shales, sandstones, and

carbonate rocks, then in terms of minerals, and finally in terms of chemical constituents.

For example, it is determined that the average analyses of shale, sandstone, and limestone should be combined in the proportions of 81.7, 12.05, and 6.25, or in round numbers 82, 12, and 6, to give an analysis as nearly as possible like that of the average igneous rock. If the average igneous rock is represented by some combination of granite and basalt, these being the most widespread types of igneous rocks, it should be possible, say the authors, to determine what proportions of granite and basalt will give an average that could be approximated by some combination of shale, sandstone, and limestone. For their granite and basalt analyses they use the average values computed by Daly. But this brings in a loose use of the terms granite and basalt, due to the fact that Daly's averages were computed from analyses of rocks which were not in every case actually granites and basalts but which had simply been given these names (in many cases certainly not in their modern sense) by the various geologists describing them. Instead of using these average analyses, it would have been much better if analyses only of rocks which are unquestionably granite and basalt had been used, even if they had been fewer in number. Thus the analysis on page 66, recomputed into the modal minerals (page 74), gives for granite a rock containing but 17 per cent of orthoclase while it carries 35 per cent of oligoclase ($Ab_{74}An_{26}$), besides biotite 6, muscovite 6, hornblende 2.5, quartz 31, magnetite 1.7, and ilmenite 0.3. The proportions of orthoclase to oligoclase are 17:35.5, making the rock a granodiorite, according to Lindgren's original definition, but just over the line from quartz-monzonite. (The orthoclase here forms 32.4 per cent of the total feldspar; Lindgren's division line is $33\frac{1}{3}$ per cent.) The basalt, also, has for its modal feldspar oligoclase ($Ab_{70}An_{30}$), and has 10.7 per cent orthoclase, besides augite 37, olivine 7.6, magnetite 5.8, ilmenite 0.73, and titanite 2.8. For a basalt the plagioclase is decidedly sodic, and the rock should rather be called a melanocratic orthoclase-bearing olivine-diorite. Comparing the modal minerals of these rocks with those in Clarke's average igneous rock, the authors found that the latter was too low in quartz, assuming that the normative quartz in 84 granites (Q=32.8) is the same as the modal. But normative quartz is almost invariably higher than modal. If analyses of true granites and true basalts were used instead of granodiorite and orthoclase-bearing olivine-diorite, the authors' and Clarke's averages would be more nearly alike. It is true that the modes given for these rocks were calculated from the

analyses, but the authors themselves say the computations represent "as nearly as possible the actual mineral composition of the rocks." Changing the granite (granodiorite) and basalt (diorite) analyses would probably give a different result for the average sediment, the proportions now found being 65 granite to 35 basalt.

Under the term anamorphism are included cementation, metasomatic replacement, rock-flowage, contact and thermal metamorphism, and the constructive changes which tend to make rocks coherent and crystalline. The anamorphism of clays through shale, slate, and schist to the contact phase, and of sands to sandstones and quartzites, and limestones to marble are all shown by numerous straight-line diagrams. Dolomitization is briefly touched upon.

In the fourth chapter of Part II, the dynamic and contact metamorphism of igneous rocks (rock-flowage) is treated. Changes produced in katamorphosed products of igneous rocks are clearly anamorphic, but igneous rocks do not necessarily pass through a katamorphosed state before becoming schists and gneisses. In such cases the katamorphic agents must in some way be simultaneously introduced. Alteration by hot water in the deeper zones is essentially anamorphic.

In the chapter on the textures and structures of dynamic metamorphism, rock-cleavage is regarded as the result of the orientation of mineral-grains or of the parallel arrangement of mineral-cleavages. The orientation of the mineral-grains is ascribed by the writers to differential pressures which caused the rock to flow. Recrystallization and the development of new minerals at right angles to the pressure and granulation and rotation of original minerals from random positions are also contributing factors in producing schistosity.

Secondary porphyritic textures, as shown by garnets, staurolite, andalusite, etc., are thought to have been caused by recrystallization, which took place after rock-flowage had ceased but while the rock was probably still under high pressures and temperature. The development of gneissic textures is considered, and Becke's and Grubenmann's views on the conditions of development of the crystalline schists are presented.

Part III treats of the determination of the origin of the metamorphic rocks. The first two parts of the book were devoted to the changes produced by metamorphism in sedimentary and igneous rocks. In this part the field and laboratory methods used in determining the origin of these rocks are discussed. Only four pages are devoted to the criteria of origin of sediments and residual rocks; a thorough treatment of this

part of the subject, say the authors, would involve the consideration of a wide range of conditions entering into sedimentation, such as is beyond the scope of the book. Twenty-two pages are devoted to primary gneisses and schists; the term primary gneisses being used for banded igneous rocks whose banding was produced during the consolidation of the rocks (ortho-gneisses, in part), and metamorphic gneisses for those that were formed by anamorphic processes (para-gneisses, in part). Among the criteria given for distinguishing primary from metamorphic gneisses are field relations, textures and structures, and mineral and chemical compositions. Instructive triangular diagrams are given showing the igneous or sedimentary characteristics of a rock.

A number of chapters are devoted to ocean, lake, river, and underground solutions as by-products of the metamorphic cycle; and there is a discussion of the metamorphic cycle as a basis for the genetic classification of commercial mineral products.

The last chapter of the third part deals with the net results of the metamorphic cycle, and the answer to the question, "Is the metamorphic cycle closed?" is that "adequate evidence of it is lacking . . . . such evidence as there is points rather toward the incompleteness of the cycle."

The fourth part, on laboratory work in metamorphism, is one of the most useful and instructive in the book. It treats of the megascopic and microscopic study of specimens and the measurement of specific gravity and porosity, a plate being given for calculating the porosity from the moisture of saturation and the specific gravity of the rock materials. It shows how analyses may be compared to determine the relative and absolute gains and losses of constituents, and gives instructions for the use of various straight-line and circular diagrams. There are instructions for comparing analyses by means of rectilinear co-ordinates, and for constructing triangular diagrams of various kinds. The determination of mineral compositions of rocks from their chemical analyses by recalculation or by the mineral slide-rule, and the calculation of volume- and energy-changes are treated, and finally there are suggestions for laboratory study.

The book is strongly recommended, not only to students of metamorphic geology, but to all students of petrology and to advanced students in economic or general geology. The authors are to be congratulated on having presented the subject in a clear, simple, and, at the same time, most interesting way.

LEISS, C., and SCHNEIDERHÖHN, H. *Apparate und Arbeitsmethoden zur mikroskopischen Untersuchung kristallisierter Körper.* Handbuch der mikroskopischen Technik, Part X, pp. 94, figs. 115.

A manual giving in simple form the more important apparatus and methods for the microscopical determination of crystals. The authors say in the preface that the book is intended only for the use of amateurs, teachers, and collectors of minerals who wish to make use of the polarizing microscope. It is, however, a book that can be read with profit by the average student of petrology. The authors not only deal with the polarizing microscope, but describe the preparation of thin sections, the use of the axial angle apparatus, refractometer, etc. The theoretical discussion is simply presented and good, and embraces all the essentials.

MEAD, W. J. "Occurrence and Origin of the Bauxite Deposits of Arkansas," *Econ. Geol.*, X (1915), 28–54, pls. 5, figs. 7.

The writer believes that the bauxite of Arkansas is derived from the weathering of the underlying syenite, and gives analyses showing the transition. Previous writers maintained that the deposits were chemical sediments or due to the action of hot springs from the still heated syenite.

MENNELL, F. P. *A Manual of Petrology.* Chapman and Hall, London, 1913. Pp. iv+256, figs. 122.

This little book is an enlargement of Mennell's *Introduction to Petrology*, which was published in 1909. The book has been practically rewritten, new cuts have been added, and the form has been considerably changed. Fifteen pages are devoted to the general properties of minerals, 11 to optical methods of determination, 53 to the rock-forming minerals, 38 to general petrology, 56 to the igneous rocks, 12 to the sediments, 32 to metamorphism, 7 to weathering, 10 to the distribution of the chemical elements, 9 to radio-activity, and 7 to the collection and preparation of material.

MERWIN, H. E. "Measurement of the Extraordinary Refractive Index of a Uniaxial Crystal by Observations in Convergent Light on a Plate Normal to the Optic Axis," *Jour. Washington Acad. Sci.*, IV (1914), 530–34.

MILLER, WILLET G., and KNIGHT, CYRIL W. *The Pre-Cambrian Geology of Southeastern Ontario.* Report Bureau Mines, XXII, Part II, Toronto, 1914. Pp. vi+151, figs. 67, pls. 4, maps 7, bibliographies.

The oldest rocks of the region are essentially green schists of igneous origin, which were extruded during the Keewatin period. In other parts of Ontario this was a period of great volcanic activity, and enormous quantities of rock were erupted. Succeeding this active period came one of sedimentation during which the Grenville series, variously estimated at from 50,000 to 94,406 feet in thickness, and consisting of crystalline limestone, greywacke, quartzite, and slate and iron formations, was laid down. During Laurentian times both the Keewatin and Grenville rocks were invaded by great masses of granite and syenite. This caused a folding and crumpling of the older rocks, and their alteration to schists and gneisses. Injection schists appear in certain places. Later, erosion removed much of the Keewatin and Grenville material and exposed the deep-lying igneous rocks. The region now became partially or entirely submerged and beds of conglomerate and quartzite of the Hastings series were deposited. The youngest pre-Cambrian rocks are post-Hastings, and include granite, diabase, and basalt. During the Paleozoic the surface sank below sea-level, and limestones, sandstones, and shale were deposited, and these were later elevated to their present position.

Numerous analyses are given, but little attempt has been made to describe the rocks petrographically.

Reviews

Geologic Atlas of the United States: Leavenworth-Smithville Folio, Kansas-Missouri. By HENRY HINDS and F. C. GREENE. U.S. Geological Survey Geol. Folio No. 206. Pp. 12, maps, ills. Washington, D.C., 1917.

This folio covers a part of northeastern Kansas and northwestern Missouri, and is traversed by the Missouri River. The rocks exposed are all Pennsylvanian, but embrace four formations—Kansas City, Lansing, Douglas, and Shawnee—in order of age from older to younger. The lower two are largely limestone, the third largely shale, and the fourth chiefly shale, capped by sandstone. They show very little tilting or disturbance. The Douglas formation includes thin and unimportant beds of coal. Borings have penetrated coal beds of greater thickness (up to 36 inches) in formations not exposed. These are found at various levels from 600 to 1,200 feet depth. Five coal mines have an annual production of 300,000 tons of hard bituminous coal. The limestone formations include much rock suitable to yield a "good grade of high calcium lime."

These quadrangles fall just inside the limits of Kansan glaciation. The post-Kansan erosion, however, has been so great that the glacial deposits are reduced to narrow strips along the divides, and small patches on the valley slopes. The thickness of the drift where it is best preserved on the main divides is nearly 100 feet, and it is not unlikely that there was originally about that thickness over the whole surface. In that case erosion has removed nearly 90 per cent of the glacial formation. There has also been some rock erosion by the Missouri and its tributaries in post-Kansan time, but in the reviewer's opinion much less than is set forth in this folio.

It has long been known that the Missouri River is made up of streams which were thrown into this drainage basin by glaciation in the Dakotas. The Missouri is thus using in this part of its course the valley of a small stream, smaller perhaps than Kansas River, which it joined at the site of Kansas City. The convergence of drainage in the quadrangles covered by this folio is toward the south part of the Leavenworth quadrangle, nearly down to the junction with Kansas River. The main streams seem also to be following courses that had been established long

before the Kansan stage of glaciation. The topographic maps seem to give no warrant for the view expressed in this folio that Missouri River was thrown across a col to connect with Kansas River at a time not earlier than the Kansan stage. Certain gravel deposits found at Weston, Missouri, and at widely separated intervals farther east are interpreted in this folio to be the product of a small stream flowing eastward from the present line of the Missouri at Weston, during the Aftonian stage of deglaciation, and a sketch map (Fig. 8) is introduced to illustrate this conception. The reviewer noted when in field conference with the junior author in 1913, and it will also be seen by descriptions given in the text, that insufficient evidence has been obtained to establish any stream connection between these widely separated exposures of gravelly material. It seems remarkable, therefore, that such a fundamental interpretation as that of the shifting of the course of one of the largest streams on the continent is here suggested. In the reviewer's opinion these gravel beds were deposited in places where water chanced to be issuing from the border of the melting Kansan ice sheet, in some cases at levels considerably above those of the neighboring valley bottoms. In exposures on the Kansas City and St. Joseph electric line south of Platte River, which are included in the supposed stream deposits, the beds dip southward directly away from the valley. In these exposures there is only a gummy, slightly pebbly clay above the gravel, such as Shimek has referred to water action and named Loveland formation. Hence it is not certain that these particular gravel deposits were overridden by the Kansan ice.

There is a reddish silt deposit covering part of the Kansan till on the upland which is referred in this folio to the Loveland formation, and, following Shimek, is classed as a water deposit. So far as the reviewer has had opportunity to study this reddish silt in Iowa and northwestern Missouri he has failed to see any clear evidence that it was laid down in water. It is a very different deposit from the gummy, pebbly clay that overlies the gravel deposits above noted, being looser textured and free from pebbles. It may prove to be a loess of greater age than the widespread, commonly recognized loess of that region. The reddening seems likely to have been produced by deep oxidation in the warm interglacial stage between the Kansan and Illinoian stages of glaciation. The loess above it is mainly of brown color, but includes layers and lenses of bluish loess in its lower part. This loess was not laid down until the Kansan drift had been greatly eroded, and is probably of similar age to the loess of eastern Iowa and western Illinois, which covers the black soil (Sangamon) formed on the Illinoian till sheet.

Frank Leverett

The Geology of the Lake District and the Scenery as Influenced by Geological Structure. By J. E. Marr. Cambridge: Cambridge University Press, 1916. Pp. 220, figs. 51, map in pocket.

The English Lake District is well adapted to call forth the interest of the geological student by reason of the variety of its geological structure and the significance of its physical features. As an increasing number of those interested in geology visit it each year, and the need of a special treatise upon its geologic features has come to be felt, the author has prepared a condensed account of the geology of this picturesque area.

The Lake District proper is composed of Lower Paleozoic strata, but its borders are formed of a roughly annular girdle of newer strata, partly of Carboniferous age, but partly belonging to the Permian and Triassic. The Lower Paleozoic rocks were profoundly affected by the great Caledonian orogenic disturbance at the close of the Silurian. Great overthrusts of the Scottish Highland type appear to have developed here also, though the author considers "lag fault" as an alternative hypothesis in the explanation of the observed phenomena.

The last third of the book describes and discusses the critical features of the Pleistocene ice sheet, which, by its erosive and depositional work, has contributed so much to the beauty and interest of this celebrated region.

R. T. C.

Origin of the Iron Ores at Kiruna. By Reginald A. Daly. Vetenskapliga och praktiska Undersökningar. Lappland. Anordnade af Loussavaara—Kürunavaara Aktiebolag. Geology No. 5. Stockholm, 1915. Pp. 1–30, figs. 4.

Professor Daly, thoroughly familiar with the writings of Geijer, Stutzer, and others, has made a short field study of the Kiruna district, particularly of the nature and origin of the numerous small inclusions of iron ore scattered through the quartz porphyry which forms the hanging wall of the ore bodies. These are commonly held to be xenolithic inclusions derived from an older invisible ore body, but the writer concludes, as a result of his field study, that the ore inclusions represent so many frozen-in units of differentiation modified in part by later resorption. The ore bodies are believed to have formed by the gravitative assemblage of similar units at the base of the quartz porphyry. Geijer has emphasized the view that both the iron ores and quartz porphyry are of extrusive origin. Professor Daly, following Stutzer,

holds that the quartz porphyry and the underlying syenite are essentially contemporaneous parts of a composite laccolith. It is suggested that the heated condition of the syenite at the time of the quartz-porphyry intrusion favored notable differentiation by prolonging the magmatic life of the later intrusive.

The origin of the ore inclusions in the porphyry is the crucial point in any hypothesis of the origin of the Kiruna ores. Professor Daly's view is a satisfactory interpretation of the field relations; likewise it accords best with recent opinion concerning differentiation processes.

H. R. B.

Journal of the Washington Academy of Sciences, V, 1915, 687 pages.

Articles of geologic interest in recent numbers of the *Journal* are: "The Paleozoic Section of the Ray Quadrangle, Ariz.," by F. L. Ransome; "Factors in the Movement of the Strand Line," by Joseph Barrell; "The Calculation of the Calcium Orthosilicate in the Norm of Igneous Rocks," by H. S. Washington; and "The Solubility of Calcite in Water in Contact with the Atmosphere, and Its Variation with Temperature," by R. C. Wells. Chase Palmer contributes an article on "Bornite as Silver Precipitant."

H. R. B.

Mineral Land Classification in Part of Northwestern Wisconsin. By W. O. Hotchkiss, assisted by E. F. Bean and O. W. Wheelwright. Wisconsin Geol. and Nat. Hist. Survey, Bull. No. 44, 1915. Pp. 376, pls. 8, figs. 39, maps 90.

This volume constitutes the report on the land classification of 87 townships in northern Wisconsin. The work was done during the field seasons of 1913 and 1914. The object of the survey was "to discover the evidence that exists as to the presence or absence of iron-bearing rocks, and as to the geologic structure of the region." The difficulties encountered either by the geologist who attempts to unravel the pre-Cambrian geology of this heavily drift-covered area, or by those who seek to locate iron ores here may be appreciated from the fact that in this area of over 2,000,000 acres the total exposed area of rocks of all kinds does not exceed 300 acres. Naturally, the report is based largely on the comprehensive series of magnetic observations.

Part I includes chapters treating of the methods of field work, general geology of the area covered, magnetic observations, land classi-

fication, and methods of exploration for iron ore. Chapter iv, on magnetic observations, gives a rather full explanation of the instruments used, the interpretation of observations made with them, and their capabilities and limitations.

Part II consists of the detailed township maps and the accompanying descriptions. Each township is fully described under the following heads: surface features, glacial drift, general geology, magnetic observations, land classification, and recommendations for exploration.

H. R. B.

Coal Resources of District VIII (Danville), Illinois. By F. H. Kay and K. D. White. Ill. State Geol. Survey, Coal Mining Investigations, Bull. No. 14, 1915. Pp. 68, pls. 7, figs. 10.

The geology of a part of this district has been described by M. R. Campbell in the Danville Folio of the U.S. Geological Survey. The present bulletin treats chiefly of the coal resources. The principal coals are in the upper Carbondale and lower McLeansboro formations. Lenticular masses of shale locally called "rolls" are common within the coal beds. Their present shape is the result of depositions in small basins and the subsequent settling of the somewhat plastic incompressible clay into the highly compressible vegetal mass. More than 58,000,000 tons of coal have been mined in this district since 1880; 1,494,000,000 tons remain in the ground.

H. R. B.

Newly Discovered Beds of Extinct Lakes in Southern and Western Illinois and Adjacent States. By E. W. Shaw. Ill. Geol. Survey, Bull. 20, 1915. Pp. 141–57.

During some parts of Pleistocene times aggradation by the Ohio and Mississippi rivers exceeded that of certain of their tributaries—those which received little glacial drainage. The valley fillings of the master-streams therefore dammed these tributaries, and lakes formed in their lower courses. The deposits that were laid down in these ponded waters are about 100 feet thick at the mouths of the tributaries and thin out upstream. The Big Muddy River is a typical case.

Shore features are poorly developed except along the Pond River near Madisonville, Ky., 50 miles from the Ohio River. The lakes were relatively short-lived, and their levels were subject to considerable fluctuations, owing to the great range of high and low water of the major streams.

There were two periods of lake development. During the intervening epoch the first deposit was almost cut through. The two stages of filling are now marked by terraces, the later of the two being 10 feet to 20 feet lower than the first.

The older of the two stages is younger than the Illinois till—probably of late Illinoian age. The other is "in or near Wisconsin time."

H. R. B.

The Ellamar District, Alaska. By S. R. CAPPS and B. L. JOHNSON. U.S. Geol. Survey, Bull. No. 605, 1915. Pp. 125, pls. 10, figs. 10.

Previous writers have considered that the copper deposits of the Prince William Sound region are genetically related to basic lavas, being formed either as concentrations of disseminated copper minerals of these greenstones or in connection with basic intrusives. The deposits are in shear zones along fault planes, principally in the greenstones. The ores carry, besides copper, some gold and silver. The minerals are chiefly sulphides, chalcopyrite, pyrrhotite, and pyrite predominating, with smaller amounts of sphalerite, galena, and arsenopyrite. The ore minerals cement or replace the shattered country rock. Quartz-filled fissures carrying similar minerals are less common. The evidence obtained indicates that the deposits were formed by primary sulphide impregnation along the fracture zones by rising magmatic solutions. Both the gold and copper veins of this region are believed to have been formed during a single period of mineralization closely following and genetically related to the late Mesozoic granitic intrusives.

H. R. B.

Mineralogy, Crystallography and Blowpipe Analysis, 5th edition. By MOSES and PARSONS. New York: Van Nostrand & Co. (1916). Pp. xiii+631, figs. 575.

The new edition has been expanded by the addition of new economic groups, by the discussion of origin and association of minerals, by added discussion of crystal optics, and by new determinative tables. The economic basis for classification is retained and emphasized, though many minerals of no economic importance are included. Perhaps the greatest difficulty arising from this classification is in the breaking up of customary crystallographic groups. For example, the rhombohedral carbonates must be sought out by looking through the calcium, mag-

nesium, iron, manganese, and zinc groups. The greatest need for improvement in the earlier editions was in the scope of the determinative tables, which have been expanded with considerable success.

A. D. B.

Microscopical Determination of the Opaque Numerals. By JOSEPH MURDOCH. Pp. vi+165, figs. 9 (index of cuts).

A determinative key for use in connection with the metallographic microscope is provided in this book. As the first work of its kind the book has already found wide use. The fundamental basis of classification is color (of the polished surface), followed by hardness and microchemical tests. A number of so-called minerals are thought by the author to represent mixtures rather than well-defined compounds, but these, with a number of unknown minerals discovered in connection with the studies on which the key is based, are given place in the key.

The book is remarkably satisfactory for a first attempt in the field, and has already made possible the use of the metallographic microscope in colleges where no research work can be undertaken.

A. D. B.

Geologic Map of West Virginia. By I. C. WHITE, R. V. HENNEN, D. B. REGER, and R. C. TUCKER. Morgantown, W.Va.: State Geological Survey, 1917.

A revised map of the state, showing coal, oil, gas, iron ore, and limestone areas, on the scale of eight miles to the inch. A list of coal mines by counties, printed on the sheet, includes those in operation up to July, 1917, except for some that are doubtless only temporary producers. The geology of areas other than those mentioned is not shown, nor is there any stratigraphic division of the limestone areas.

A. D. B.

Economic Geology, 4th edition. By HEINRICH RIES. London: Wiley & Sons, 1916. Pp. xviii+856, figs. 291, pls. LXXV.

In the fourth edition this well-known work has been considerably expanded and materially improved, both in the treatment of topics and in the descriptions of deposits. Many illuminating figures and diagrams have been added. Among the more noteworthy changes are the expansion of the chapter on petroleum and the chapter on ore deposits, and the addition of descriptions of many of the important Canadian deposits.

As with former editions, the reviewer feels a little lack of coherence between chapters—a difficulty that is perhaps insurmountable in a text of this sort.

A. D. B.

Investigation of the Peat Bogs and Peat Industry of Canada, 1911–12. By A. V. ANREP. Department of Mines, Canada, Bull. No. 9. 1914.

A detailed report of preliminary investigation of peat bogs in the provinces of Quebec and Ontario.

Coal Fields and Coal Resources of Canada. By D. B. DOWLING. Department of Mines, Canada. Memoir 59, 1915. Pp. 174, maps 7, figs. 9.

Chiefly material reprinted from "Coal Resources of the World" compiled for the Twelfth International Geological Congress.

Coal Fields of British Columbia. By D. B. DOWLING. Department of Mines, Canada, Memoir 69, 1915. Map 1, diagrams 23. Pp. 350.

Discusses the coals of the Cretaceous and Tertiary horizons in various areas of British Columbia.

E. A. S.

British and Foreign Marbles and Other Ornamental Stones. By JOHN WATSON. Cambridge: Cambridge University Press. New York: Putnam, 1916. Pp. 485. $1.50.

In addition to marble, numerous other ornamental stones are discussed, the most important being onyx marble, malachite, alabaster, fluorspar, quartzite, labradorite, lapis lazuli, serpentine, steatite, and jade. Includes brief description of the occurrences.

E. A. S.

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GENESIS OF THE ALKALINE ROCKS

REGINALD A. DALY
Harvard University

INTRODUCTION

The eruptive sequence in the compact and quite isolated igneous complex at Ascutney Mountain, Vermont, opens with gabbro and closes with dike rocks, including its chemical equivalent, diabase. The gabbro seems locally to merge into a type intermediate between essexite and a basic diorite. That body is cut by dikes of a mafic rock which shares the characteristics of monzonite and ideal essexite.[1] Intruding the gabbro, "diorite," and essexitic monzonite are several stocks or thick dikes of alkali-rich syenites, themselves cut by a stock of alkaline granite. Still younger are the diabase dikes.

The study of Ascutney Mountain, begun in 1893, introduced the writer to the problem of the so-called alkaline rocks. There he first became skeptical of the dogma that the alkali-rich magmas have originated independently of the subalkaline (lime-alkali)

[1] The relation between this microperthite-orthoclase-plagioclase rock and the gabbro-"diorite" body, described in *Bull. 209, U.S. Geol. Surv.*, 1903, was proved in 1916.

magmas. That doubt was confirmed during observations in the volcanic fields of France, Italy, and Germany, in the colossal igneous fields of the North American Cordillera, and in Hawaii.

North of the Hawaiian volcano, Hualalai, soda-rich trachyte rests on, and is surrounded by, great flows of olivine basalt. This spectacular association could not fail to recall the problem which had been so baffling during the interval of sixteen years. More than ever the writer was convinced of the extreme intimacy of the alkaline and subalkaline suites of igneous rocks. The relatively small volume of all known alkaline rock and the small absolute sizes of alkaline bodies had suggested their derivation from the overwhelming subalkaline magmas, but it was not until the Hawaiian lavas were closely considered that a promising clue to an explanation was found.

The hypothesis involving that clue was published in 1910. One outstanding fact on which the hypothesis is based is the common occurrence of feldspathoids in the alkaline rocks instead of, or alongside, feldspars, which are the dominant constituents of the subalkaline rocks. The presence of nephelite or leucite signifies a lack of silica available for full saturation of soda or potash or both, suggesting some desilication of original subalkaline magma. Secondly, the concentration of alkalies in many alkaline rocks means that some agent or group of agents had collected the alkalies from the original magma. No success characterized the attempt to imagine adequate causes for the desilication or for the enrichment in alkalies, if the magma remained throughout purely juvenile in origin. The writer was thus led to assume the absorption of foreign material as the responsible condition. Such material is basic sedimentary rock. The most basic, large-scale, and widely spread rocks are limestone and dolomite. Also on account of the relative chemical simplicity of the carbonates the writer laid stress on these particular sediments. Unfortunately certain authors have thought that it was intended to explain all alkaline rocks by the interaction of resurgent carbonates with subalkaline magma, though that was disclaimed in the original paper.[1] In 1913 the hypothesis was elaborated and the very important case of the

[1] *Bull. Geol. Soc. Am.*, XXI (1910), 108, 113, 114, 116.

syenites was speculatively treated. For those rocks, the most voluminous of the whole alkaline suite, *hydrous*, *basic* sediments (with or without calcareous associates) were considered as the probable agents of desilication and concentration of alkalies.[1] Thus, while the absorption of small amounts of limestone or dolomite seems to be the chief cause for the differentiation of most nephelitic and leucitic rocks, many other alkaline types were explained by the assimilation of hydrous sediments, in indefinitely varied mixture with one another or with more siliceous rocks or with carbonate rocks.

During the last four years new field observations and some experimental work bearing on the subject have been reported, and important papers on general theory as well as on special points have been published. A review of these matters and correlated observations of older date is the purpose of the present article. A full discussion of the origin of alkaline rocks is not attempted, but rather a supplement to corresponding chapters in the writer's *Igneous Rocks and Their Origin.* After brief discussion of the field and chemical studies, Bowen's petrogenic theory, the strength of which is so largely measured by its ability to explain the alkaline rocks, will be analyzed in some detail.

RECENT FIELD OBSERVATIONS

Many investigators of alkaline rocks still continue to give merely petrographical descriptions. Others discuss the origin of the rocks, but are content to refer the various types to differentiation without giving any adequate idea of what was differentiated. A few writers during the last four years have more seriously considered the questions of origin, and it is worth while to note their findings.

Relation of the alkaline and subalkaline suites.—From new localities have come proofs of the exceedingly close time and space associations of the alkaline ("Atlantic") and subalkaline ("Pacific") eruptives. Among those who have lately laid emphasis on the point are Lacroix, Smyth, Cross, Washington, Holmes, Bowen, Harker, and the writer.[2]

[1] R. A. Daly, *Igneous Rocks and Their Origin* (New York, 1914), p. 395.

[2] A. Lacroix, *Bull. soc. géol. France*, X (1910), 91; *Comptes rendus*, CLV (1913), 538; C. H. Smyth, *Amer. Jour. Sci.*, XXXVI (1913), 41; W. Cross, *Prof. Paper 88, U.S. Geol. Surv.*, 1915, pp. 85, 91; H. S. Washington, *Compte rendu, Cong. géol. internat.*

The cited paper by Washington is worthy of special mention. He is certainly right in pointing out the vague nature of the expression "alkaline suite." The recognized difficulty of assigning some rocks to it rather than to the subalkaline suite matches the perfect transition between the two series. The use of these names involves danger to correct thinking if, while using them, the petrologist does not resist the idea that the two distinct suites really existed as such from the earth's beginning. Nevertheless some general name for alkali-rich rocks and their syngenetic associates is useful, and "alkaline" will be here so employed.

An illustration of the bond between the two suites is seen in the relation of albite-rich or oligoclase-rich lavas, the so-called spilites, to normal basalt, dolerite, or diabase.[1] Sargent has just proposed the term "auto-metamorphism," symbolizing his conclusion that the Lower Carboniferous spilites of Derbyshire have been derived from common basaltic magma through the "retention of volatile constituents resulting from the physical environment of a submarine flow."[2]

Though a follower of Becke in his interpretation of the "Atlantic" and "Pacific" suites, Winkler sees the intimacy of the two in the Eastern Alps (Steiermark). There the Pliocene was a time of extrusion of "Atlantic" magma, from which nephelite regularly crystallized. Winkler explains contemporaneous rock types more characteristic of the "Pacific" suite (normal basalts) by silication due to the solution of quartzose sediments in the original "Atlantic" magma.[3]

Ice River intrusion, British Columbia.—Allan states that the Ice River intrusive furnishes "a very strong case in favour" of the sediment-syntectic hypothesis (desilication) as applied to nephelite syenites and their allies—an explanation squarely opposed to that

(Ottawa, 1914), p. 235; A. Holmes, *Mineral. Mag.*, XVIII (1916), 71; N. L. Bowen, *Jour. Geol., Suppl.*, XXIII (1915), 59; *ibid.*, XXV, 220; A. Harker, *Jour. Geol.*, XXIV (1916), 556; R. A. Daly, *Bull. Geol. Soc. Am.*, XXVII (1916), 329.

[1] Cf. S. von Szentpétery, *Mitt. Mineral. Geol. Sammlung des Siebenbürg. Nationalmuseums*, Kolozsvar, Band I, No. 2, 1912.

[2] H. C. Sargent, *Nature*, XCIX (1917), 59; *Phil. Mag.*, XXXIII (1917), 535.

[3] A. Winkler, *Zeit. für Vulkanologie*, I (1914), 182.

given by Winkler for the Alpine rocks just mentioned. In order to reach its present position the magmatic material at Ice River "had to travel through at least 10,000 feet of limestone or highly calcareous sediments of Cambrian age, and 3,000 feet of more or less calcareous shales."[1] Allan also finds evidence of resurgent carbon dioxide, volatilization of the alkalies, and gravitative adjustment in this remarkable complex. Large xenoliths of shale and limestone show plainly (p. 190) the introduction of alkaline solutions, which have caused in the xenoliths the crystallization of feldspars, nephelite, sodalite, and cancrinite, along with many lime minerals.[2]

Haliburton County, Ontario.—Foye has made a very important contribution to the subject as a result of his study of the nephelite syenites and adjacent formations in Haliburton County, Ontario.[3] Adams and Barlow had proved a large part of the associated amphibolites and pyroxenites to be due to the contact metamorphism of thick limestones by numerous granitic sills and "batholiths" (these described by Foye as laccoliths).[4] Foye was able to show that the magmatic emanations so largely responsible for this profound metamorphism were very like the material that went to form the nephelite syenite of the region. The total volume of the amphibolites thus formed is many times greater than the total volume of the nephelite syenite, making all the more probable the view that this alkaline rock has been formed pneumatolytically. Foye goes farther and concludes that the gases engaged in segregating the alkalies included resurgent carbon dioxide (and water), derived from the limestones and other interbedded sediments as these reacted with the granitic magma. Granite injections and limestones together made a "gigantic steam pack," from which alkaline volatile matter was expelled. Part of this formed a large proportion of the amphibolite; a much smaller part was trapped

[1] J. A. Allan, *Memoir 55, Geol. Surv. Can.*, 1914, p. 211.

[2] Compare the nephelitic schliers and nephelite-lined vugs in the nephelite basalt of the "Löbauer Berg," described by J. Stock, *Tschermaks Min. und Petr. Mitt.*, IX (1888), 438.

[3] W. G. Foye, *Amer. Jour. Sci.*, XL (1915), 413.

[4] W. G. Foye, *Jour. Geol.*, XXIV (1916), 783.

in the sill and laccolith chambers and finally crystallized as nephelite syenite and its by-products.

The crescentic laccolith near Tory Hill illustrates gravitative differentiation, also well displayed in several other of the thicker alkaline bodies. The maximum thickness of the laccolith is only about three hundred feet, yet it shows a striking variation from top to bottom as here indicated:

a) Pegmatitic nephelite syenite, with specific gravity of 2.674; carries microperthite (59 per cent), nephelite (21 per cent), and albite (12 per cent); contacts with limestone roof.

b) Monmouthite, with specific gravity of 2.719; carries nephelite (57 per cent), albite (9 per cent), scapolite (10 per cent), and biotite (22 per cent).

c) Hornblende-nephelite rock, with specific gravity of 3.124; carries nephelite (30 per cent), albite (7 per cent), pyroxene (20 per cent), hornblende (30 per cent), garnet (7 per cent), and primary calcite (5 per cent).

d) Garnet-pyroxene rock, with specific gravity of 3.383; carries albite (3 per cent), pyroxene (34 per cent), garnet (37 per cent), and primary calcite (25 per cent); contacts with limestone floor.

The mineralogical composition of the Tory Hill and other laccoliths of the district directly indicates the probability of syntexis between magma and limestone. Of course there is no necessity of assuming that all, or even the larger part, of this assimilation took place at the visible contacts.

Palingenesis in relation to the problem.—Basaltic magma may not at all have participated in these Ontario developments. The writer suspects that, like many other pre-Cambrian invasions of magma, the petrogenic cycle was not opened by the abyssal injection of basalt. Along with Lawson, Sederholm, and other workers in pre-Cambrian complexes, one is rather tempted to regard the activity of the granite magma as due to palingenesis, that is, refusion of the crustal granite at a level not far below that to which erosion has brought the general surface of Haliburton County. This whole field exemplifies the difficulty of applying to the granites of the older pre-Cambrian terranes any petrogenic scheme that

may succeed in explaining post-Cambrian eruptive bodies and sequences.

Azof region, Russia.—Guinsberg believes that the limestone-syntectic hypothesis is valid for the nephelitic and other alkaline rocks studied by him in the Azof (Mariupol) region, even though they do not make visible contact with limestones at all. He

explains the origin of the nephelite-syenite by the mixture of a basalt-magma with limestone followed by a differentiation in alkali rocks and pyroxenite. Although the limestones were not discovered in this district, the presence of sedimentary rocks such as quartzite was established. In the neighboring district of Berdjansk, which forms the continuation of the same crystalline area, Morozewicz found among the crystalline schists together with quartzites also limestone and graphitic gneiss.[1]

Reinhardswald, Germany.—Apel's recent work on the Reinhardswald district of Northern Germany gives the petrography of a large number of volcanic necks.[2] The eruptives include: common basalt, dolerite, enstatite dolerite, trachydolerite, nephelite basalt, melilite-bearing nephelite basalt, leucite basalt, leucite basanite, limburgite, and nosean-bearing limburgite. Other types represent the transition between nephelite basalt and leucite basalt.

This assemblage claims notice as another example of the close connection between alkaline varieties and feldspar basalt. Lepsius' geological map of Germany seems to show that the alkaline-lava vents are here largely or wholly confined to areas underlain by the Muschelkalk at the time when the volcanoes were active, numerous vents filled with feldspar basalt and dolerite appearing specially in Bunter Sandstein areas. The writer has not been able to check this generalization by reference to a large-scale geological map of the region, but has thought the question involved might well be put on record. In any case the possible chemical influence of the Muschelkalk on the magmas which fluxed, stoped, or exploded their way to the earth's surface needs investigation. The problem is complicated on account of the partial removal of the limestone by erosion since the volcanic epoch.

[1] A. Guinsberg, "Pierre le Grand à Pétrograde," *Annales de l'Inst. Polytech.*, XXV (1916), 435.

[2] K. Apel, *Neu. Jahr. für Mineralogie*, etc., B.B. XXXVIII (1914), 525.

Almunge, Sweden.—Among the most noteworthy publications of late years is Quensel's paper on the alkaline rocks of Almunge.[1] Consisting of dominant umptekite with an aplitic marginal zone and with huge inclusions of canadite (albite-nephelite syenite), these rocks form a stocklike body measuring 4.5 by 3.5 km. It cuts granite of two types. Quensel's memoir is full of valuable information, but two chief points are of present importance. One is the abundance of the two lime minerals, vesuvianite and primary cancrinite, in the canadite. The other is Quensel's suggestion as to the genesis of this rock. His statement may be quoted (p. 196):

Vesuvianite has always been considered a typical mineral of the contact metamorphism of calcareous rocks. It seems difficult to explain its presence in the Almunge canadites in any other way than that it represents the remains of otherwise fully assimilated calcareous sediments. Its occurrence would then be comparable with the primary calcite of Alnö or Bancroft, formed through assimilation of limestones by the igneous magma under such circumstances that the CO_2 could not abscond. The very essential amount of cancrinite in all these rocks would then probably be a manifestation of the same geological features. The presence of a hydrated mineral in an igneous rock is hardly more remarkable than CO_2 partaking in the constitution of other magmatic minerals under similar circumstances.

Though nothing can be said with certainty about the origin of the alkaline rocks, several features seem, however, to point to the possibility of the origin of nepheline-syenites in some way having been connected with the assimilation of calcareous sediments. As previously mentioned, paragneisses with interbedded limestone are found at no very great distance south of the area and may possibly be present at deeper levels within the Almunge district itself.

The writer is free to admit that future field work at a number of other localities is not likely to yield results positively favorable to the sediment-syntectic hypothesis for the alkaline rocks. Yet the

[1] P. D. Quensel, *Bull. Geol. Inst. Upsala*, XXII (1914), 129. While the proofs of the present paper were being read, Thorolf Vogt's account of the rocks of Hortavaer, Norway, reached America [Videnskapsselskapets Skrifter, I Mat.-naturv. Klasse, Christiania (1915), No. 8]. Vogt describes the peripheral solution of large limestone masses in intrusive subalkaline magma, with the resulting generation of alkaline pyroxenes which chiefly compose "hortite," a new plutonic type. He concludes that the injection temperatures were in the neighborhood of 1300° C. for the intrusives at Hortavaer and at Alnö, Sweden! Still other features of Vogt's paper are significant in connection with the sediment-syntectic hypothesis, which he regards as sound at least in part, but space fails for a fuller discussion of this careful petrological study.

apparent or real absence of basic sediments at those places is not immediately compelling to anyone who remembers the complex conditions due to deep erosion, to inadequate exposures, to "staccato" injection,[1] to the lateral migration of magmas, as proved in the case of sill or laccolith, and to the probable fact that most pre-Cambrian granite (and orthogneiss) has been concordantly injected and may therefore in a given instance cover thick, basic sediments not locally exposed. The last-mentioned principle affects the negative evidence for appropriate country rocks around the alkaline eruptives of the Julianehaab district, the Kola Peninsula, Cripple Creek, certain localities in New Hampshire and East Africa, etc.

The repeated objection that some granites, granodiorites, and other subalkaline bodies cut limestones and yet do not show obvious chemical reaction with the sediments is not necessarily valid. Such contacts may simply indicate the respective magmatic temperatures to have been too low for the reaction. Before stoping or other mechanical movements had established any of these contacts the temperature may have been higher, so that solution of limestone was then possible. However, unless the limestone made a considerable part of the whole rock mass dissolved (otherwise likely to be composed of siliceous country rock), the effects of the solution of limestone might be masked by the differentiation of each great body of magma. In a special case a batholith may have stoped its way to the limestone just as the dissolving power of the magma was approaching zero.

Hawaii.—Cross's valuable memoir on the Hawaiian lavas bears the conclusion that the alkali-rich rocks and melilitic rocks of the archipelago are "products of the same general process of differentiation [of original basalt] as the other rocks with which they are associated."[2] He rejects the sediment-syntectic hypothesis, partly because he doubts that limestones are "associated with the older lavas of the archipelago." He fails also to see how "superficial deposits of coral limestone . . . . can gain access to the volcanic conduit in mass sufficient to produce any notable result." Yet

[1] Cf. R. A. Daly, *Amer. Jour. Sci.*, XLIII (1917), 444.

[2] W. Cross, *op. cit.*, p. 90.

thick limestones do underlie the lavas of Oahu, and it is scarcely credible that during the slow growth of the volcanic piles through 2,500 fathoms of warm Pacific water there should be no interbedding of calcareous oozes, coarser shell deposits, or coralliferous limestones. The magma of a volcanic vent, locally fluxed through such a composite, could not fail to incorporate some calcareous material. The remaining question is as to how much assimilation is "sufficient to produce any notable result." The answer is—comparatively little. Since alkali-rich rocks are very rare in Hawaii and, so far as known, of small individual volumes, the absolute amount of limestone assimilation need be very slight and in any case quite local.

The syntexis of basalt and limestone is positively suggested by the several occurrences of nephelite-melilite basalt in and around Honolulu, where deep borings have proved the existence of thick limestones which must have been traversed by the conduits of these lavas. In the same region are nephelite basalts. As Cross states, it may be "certainly true that the alkali-rich lavas are not present about Honolulu," but the first step in limestone syntexis is obviously not an alkali-rich magma. That can originate only under conditions allowing drastic differentiation. According to the present writer's view, the flows of melilitic and nephelitic basalts are quenched phases, erupted before much concentration of alkalies in the vent was possible. As Bowen agrees, melilite is possibly a direct sign of syntexis with limestone rather than of pronounced differentiation. Ten years ago Becker published the hypothesis that the melilite in the basalts of the Wartenberg and of Southwest Germany in general have resulted from the absorption of calcareous sediments.[1]

Tahiti.—Marshall, by actual field work, has well supplemented Lacroix's petrographic studies in Tahiti.[2] In the central pipe of the island he found an alkali-rich syenite associated with wehrlite and gabbro. This stocklike or necklike body traverses the flows

[1] Cf. N. L. Bowen, *op. cit.*, Suppl., XXIII (1915), 89; R. A. Daly, *Igneous Rocks and Their Origin* (New York, 1914), p. 436; E. Becker, *Zeit. deut. geol. Gesell.*, Band LIX (1907), 273.

[2] P. Marshall, *Trans. New Zealand Inst.*, XLVII (1915), 361.

of dominant, common basalt. The syenite and other alkaline types have suggested the problem of origins to Marshall. He finds no evidence favoring the sediment-syntectic hypothesis in this case. A chief ground for doubting it is the assumed lack of limestone in the volcanic pile. Marshall admits that globigerina ooze veneers the submarine flanks of Tahiti, but implies that neither ooze, coralliferous limestone, algal limestone, nor shell limestone was interbedded with the basaltic flows during the slow submarine growth of the volcano. Again one must ask if such interbedding can, under the tropical conditions, possibly be doubted. Again, too, the required amount of assimilation of limestone and other sediments would be small.

Queensland.—Richards has published an excellent study of the Tertiary volcanic rocks of southeastern Queensland.[1] These are divisible into three stratigraphic divisions. The lowest is composed of common basalts. The middle division includes augite andesite, rhyolite, comendite, trachyte, soda-trachyte, phonolitic aegirite trachyte, and pantellerite. The upper division is dominantly basaltic, with flows of olivine basalt, olivine-free basalt, andesitic basalt, oligoclase basalt, and andesite. The alkaline rocks "constitute at the most 5 per cent of the volcanic material." Richards regards all types as mere differentiates of a single original magma and follows the all too common plan of calculating its composition from the volumes and compositions of the visible rocks only. Inasmuch as no reckoning is made of the other magmatic phases that must have remained in the magma chambers below the earth's surface, the estimate is entirely misleading and, for its purpose, of no immediate value.[2]

On account of the relatively small amount of limestone in the country rocks, Richards finds unsatisfactory the sediment-syntectic hypothesis in explanation of the Queensland alkalines. However, limestone is not necessarily a partner in a syntectic from which trachytes, pantellerites, or comendites are differentiates. The writer has indicated the grounds for regarding shales and other subsiliceous, hydrous sediments as more influential in the generation

[1] H. C. Richards, *Proc. Roy. Soc. Queensland*, XXVII (1916), 105.

[2] The same principle applies to alkaline provinces in general.

of trachytic and syenitic magmas generally.[1] The solution of small amounts of Mesozoic and Paleozoic non-calcareous sediments (or of their connate waters) in basaltic magma may be primarily responsible for the quite subordinate, alkali-rich lavas of Queensland. The traces of calcareous material in these sediments might co-operate in the underground reactions, but carbonates were not in chief control.[2]

SPECIAL CHEMICAL CONSIDERATIONS

"Saturation" in igneous rocks.—Shand expresses a suggestive idea in distinguishing "saturated," "undersaturated," and "oversaturated" igneous rocks.[3] Saturated rocks are those that contain only minerals which are capable of forming in the presence of free silica. Any rock containing free quartz or tridymite of magmatic origin is said to be oversaturated. Undersaturated rocks are composed, wholly or in part, of minerals unsaturated with silica. Shand's list of unsaturated minerals includes leucite, nephelite, sodalite, nosean, analcite, cancrinite, hauyne, melanite, melilite, magnesian olivine, corundum, and perovskite—all characteristic components in alkaline rocks.[4]

One of the causes for undersaturation Shand finds in assimilation. He writes (p. 511):

> When the invaded rock is a carbonate or other non-silicate rock, or contains much lime, magnesia, or iron in the form of oxide or carbonate, then the advantage as regards absorbing power lies with the saturated and oversaturated magmas, which can yield first their excess of silica, and secondly a further quantity of silica due to the reduction of sodium, potassium, calcium, and magnesium molecules from the saturated to the unsaturated state. In this way a saturated or oversaturated magma may become undersaturated.

[1] R. A. Daly, *Igneous Rocks and Their Origin* (New York, 1914), pp. 393, 410.

[2] The remark of Richards (p. 190), that "Dr. Jensen has also advocated the assimilation of carbonate rocks by the parent magma with the resultant production of alkaline material," is hardly a correct rendering of Jensen's hypothesis. Jensen assumes the precipitation of "alkaline salts" to the floor of the primitive ocean, their burial, and their later fusion and fluxing with the silicates of the overlying rocks. The present writer has not "elaborated this view," as Richards states.

[3] S. J. Shand, *Geol. Mag.*, X (1913), 508.

[4] See J. Morozewicz, *Tschermaks Min. und Petr. Mitt.*, XVIII (1898), 224. A. Holmes (*loc. cit.*, p. 71) points out that the basalts associated with the alkaline lavas of East Africa are also undersaturated with silica.

He favors the view that this condition applies to many alkaline rocks.

Among the consequences of undersaturation, according to Shand (p. 510), is the tendency of foyaitic or phonolitic magmas to enter "into chemical combination with the silica of invaded rock masses. The reactions thereby induced would be exothermic, and would tend to raise the temperature of the magma. . . . . The access of heat produced in this way would in turn enable the magma to perform a further amount of work in the way of mechanical solution." One is reminded of Ramsay's conclusion that the umptekite of the Kola Peninsula is probably due to syntexis between nephelite-syenite magma and siliceous sediments.[1] An analogy is found in Ussing's explanation of important masses of quartz syenite and soda granite in the Julianehaab district as products of reaction between augite-syenite magma and sandstone. Quensel, too, assumes syntexis between the umptekitic magma of Almunge and older granite, giving the observed transition between the corresponding formations.[2]

Shand notes the relative insignificance of alkaline rocks in volume; the dominance of oversaturated rocks among major intrusions; the dominance of saturated and undersaturated rocks (including basalts) among lavas and minor intrusions; and (p. 512) the

> strong suggestion that undersaturation may be characteristic of the deeper zones of the lithosphere, as oversaturation is of the higher. . . . . Those igneous rocks which have been brought up most rapidly from the earth's interior, and have solidified most rapidly in or on the crust, are to a marked extent undersaturated. Those which have slowly worked their way up into the crust (and have hence had abundant opportunity for absorbing silica) are found to be predominantly oversaturated.

Comparison may be made with the idea of granitic, continental maculae overlying a basaltic earth-shell.

[1] W. Ramsay, *Fennia*, XI, No. 2 (1894), pp. 74, 95. As above noted, Winkler has given proofs of the solution of quartz in basic Alpine lavas which he considers as belonging in the alkaline suite.

[2] N. V. Ussing, *Meddelelser om Grönland*, XXXVIII (1911), 59, 191, 197, 363, 366; P. D. Quensel, *op. cit.*, XII (1914), 196.

Action of "mineralizers" and of normal faulting.—Cross, Bowen, Foye, and others approve Smyth's reference[1] of the alkali-rich rocks to the work of gases or "mineralizers" operating in subalkaline magmas. The pneumatolytic origin of many nephelitic, sodalitic, and cancrinitic rocks has indeed long been clear to the French and other intelligent students of their mineralogy and texture. The next important questions are as to the origin of the gases and the cause of the concentration of the gases. Smyth regards the gases as (p. 45) "magmatic or 'juvenile' rather than resurgent" and joins Harker in thinking that their concentration along with the alkalies probably depends on crustal dislocation by radial movements in the earth.

He makes no other suggestion as to the reason why the mineralizers should, in general, not have the power to develop nephelite syenites and similarly undersaturated rocks in most plutonic complexes. Water and other mineralizers form tremendous emanations in andesitic volcanoes, yet many of these lack phonolitic, trachytic, or other alkali-rich lavas. The present writer has shown that many alkaline bodies occur in zones of intense tangential compression, while, on the other hand, subalkaline bodies are abundant in areas of radial dislocation. The statistics of distribution are far from supporting Harker's thesis. It suffers also from the improbability of another underlying assumption—that in every instance the parent subalkaline magma was nearly frozen at localities where normal faulting has caused the eruption of multitudes of small alkaline masses. The mechanism is seen to be one of almost infinite delicacy and hence of doubtful reality, at least on the scale demanded. One may observe also that normal faulting need not exert a notable squeezing-out effect if the magma chamber were not cut by the fault planes. A semiliquid mass inclosed in a downthrown or upthrown block would not necessarily undergo any differential stress. The alternation of liquid basalt and trachyte or phonolite at the same volcanic center is one of the more obvious difficulties with the speculation.

Further, the Harker hypothesis does not take proper account of the lamprophyres which usually close petrogenic cycles. While

[1] C. H. Smyth, *op. cit.*, p. 33.

aplites are explained, vogesites, spessartites, and odinites are not. If tinguaites or nephelite pegmatites represent residual liquids, what is the meaning of the camptonites or alnöites, so closely associated both in time and space with those alkaline types? In some nephelite-syenite areas camptonites not only are abundant but appear to be even younger than most of the tinguaites. There is manifest trouble in explaining *both* the salic and femic dike groups as crystallizations from residual liquid.[1]

Considering the weakness of the idea relating alkaline magmas to crustal dislocation of a special kind, Smyth's conception needs an important supplement. It would be strengthened if a more probable cause for the local, quite exceptional, concentration of the mineralizers and alkalies in purely juvenile magma were discovered. This has not yet been done. On the other hand, the local assimilation of sediments cannot, in general, fail to enrich subalkaline magmas in gaseous constituents, with the effect of segregating the alkalies, as the writer has long held.[2] In short, the combination of juvenile and resurgent "mineralizers" is believed to be a much

[1] A. Harker (*op. cit.*, p. 558) recently published a very doubtful argument in support of his contention that subalkaline ("calcic") rocks rather than alkaline rocks are genetically associated with "regions subjected to powerful lateral thrust." He writes: "If we examine those crystalline schists which are admittedly of igneous origin, together with foliated igneous gneisses, we find that they belong almost exclusively to the calcic branch. . . . . Alkaline crystalline schists as a whole are quite insignificant as compared with any single type in the calcic division. . . . . The striking disparity here noted is only one consideration among others which points to a peculiar distribution of alkaline and calcic igneous rocks in relation to crustal stresses."

Evidently the dynamic metamorphism in most of the cases cited followed *after* the respective eruptions. Some of the intervals between eruption and shearing have been proved to equal several geological periods. Can one assume that the resulting schistosity of the igneous bodies has any connection whatever with the generation of their magmas? Moreover, there is much to be said for the view that the schistosity and foliation of pre-Cambrian rocks largely originated during static metamorphism rather than during the operation of lateral thrust. It may be observed that neither great volumes nor wide distribution for the alkali-rich rocks would be expected in the older pre-Cambrian terranes by an upholder of the sediment-syntectic explanation of alkaline rocks.

[2] From the composition of the amygdale minerals in the alkaline lavas of Mozambique, A. Holmes (*Nature*, XCVIII [1916], 162) believes the corresponding magmas to have been rich in carbon dioxide as well as undersaturated in silica. The same author describes calcite inclusions in the analcite and nephelite of nephelinite at the Lucalla River, Angola, West Africa (*Miner. Mag.*, XVIII [1916], 64).

more likely cause than the action of the greatly overworked juvenile gases alone.

Migration of free volatile materials from country rock.—The addition of resurgent gas to a magma does not depend entirely on the solution of country rock as such. Elsewhere the writer has emphasized the high probability that connate water and other volatile substances in the country rock may be independently driven into injected magma.[1] An illustration is found in the so-called white traps of Scotland. Day holds that the otherwise typical basalt of the Cheese Bay sill has been reduced, whitened, and rendered vesicular by bituminous emanations from the intruded shale.[2]

Relevant experiments.—Controlled experiments on the chemical effects of dissolving limestone, dolomite, shale, etc., in subalkaline, particularly basaltic, melts are needed. They are sure to be difficult experiments if the conditions of nature are even approximated. Failing such direct tests, the information accruing from certain attempts to extract potash from feldspar commercially is not without value. According to Ross, if potash feldspar, lime (CaO), and water are heated together in a bomb at 300° C. and under a pressure of 91 atmospheres, the potassium is leached from the mineral and, as caustic potash, taken into the water solution. The amount of the leaching depends on the proportion of lime in the mixture until about three grams of lime are mixed with one gram of feldspar, when practically all of the potash is found to be leached.[3] In the same volume where Ross's paper appears (p. 646), R. J. Nestell and E. Anderson illustrate with actual analyses the strong volatilization of both potash and soda in the kilns of cement-mills. They agree with Ross in holding that the presence of lime tends to prevent a recombination of the alkalies with the silica of the original kiln charge.

Such experiments do not, of course, prove anything definite about magmatic reactions, but they do encourage the speculation that, in the presence of juvenile and resurgent water, carbon dioxide, and other volatiles, the alkali oxides may in a sense be

[1] R. A. Daly, *Amer. Jour. Sci.*, XLIII (1917), 445.

[2] T. C. Day, *Trans. Edin. Geol. Soc.*, X (1916), 249, 261.

[3] W. H. Ross, *Jour. Indust. and Eng. Chem.*, IX (1917), 467.

volatilized from a sedimentary syntectic and then concentrated either in the same magma chamber or in satellitic chambers. Whether the necessarily complex solutions will carry the alkalies free or as carbonates, aluminates, hydrates, silicates, or alumosilicates is a problem not now to be solved, but it cannot fail to be considered by the serious student of the assimilation theory.[1]

Perhaps, too, experiment may yet tell the essential reason for leucitic (potash-rich) differentiates in one body and nephelitic (soda-rich) differentiates in another. Leucite, nephelite, and sodalite accompany such minerals as garnet, melilite, hauynite, and plagioclase in industrial slags. It would be of interest to know what contrasts of crystallization there may be in artificial melts, otherwise similar but with pure calcite as the only carbonate flux of the one group of melts and pure dolomite as the only carbonate in the other. Why is albite concentrated in spilite and orthoclase in the "orthoclase basalts"?[2] The reply, that each is due to differentiation, is hardly a reply at all. One needs to know what was the *cause* of each differentiation and *what it was* that differentiated.

BOWEN'S EXPLANATION OF THE ALKALINE ROCKS

Summary of his general theory.—Basing his results on an unmatched group of experiments, Bowen has given to the world a "systematic petrogenic theory" which is deeply concerned with the alkaline rocks.[3] Since the validity of his theory on this side depends on the general mechanism assumed, a considerable amount of attention must be given to main principles before the special reasoning applied by Bowen to the alkaline suite can be properly weighed.

His views may be summarized in his own words (pp. 89, 90): "Consideration of the factors limiting its scope has led to the decision that assimilation is, relatively speaking, an unimportant

[1] Compare G. W. Morey's thorough study of the ternary system, $H_2O-K_2SiO_3-SiO_2$, reported in the *Jour. Am. Chem. Soc.*, XXXIX (1917), 1173.

[2] S. H. Reynolds, *Quart. Jour. Geol. Soc.*, LXXII (1917), 23.

[3] N. L. Bowen, *Jour. Geol.*, Suppl., XXIII, 1915.

factor in the production of the diversity of igneous rocks." He agrees with "the great majority of petrologists" that

> the rocks of any area vary among themselves in a systematic manner which indicates derivation from a common stock through some systematic process of differentiation from that stock.
>
> The decision is reached that this differentiation is controlled entirely by crystallization. The sinking of crystals and the squeezing out of residual liquid are considered the all-important instruments of differentiation, and experimental evidence is adduced to show that under the action of these processes typical igneous-rock series would be formed from basaltic magma if it crystallized (cooled) slowly enough. The characteristic occurrence of basaltic magma as regional dikes and as the material of the great fissure eruptions is considered evidence of the primary nature of basaltic magma. It is concluded, therefore, that most, if not all, igneous rocks have probably been derived from basaltic magma, the processes of differentiation that have been pointed out above emphasizing the lighter, more salic and alkalic differentiates in the upper portions of very large, slowly cooled bodies.

Definition of "differentiation."—On page 3 of his paper Bowen defines differentiation as "any process whereby a magma, without foreign contamination, forms either a mass of rock that has different compositions in different parts or separate masses that differ from one another in composition." In two respects this definition is unsatisfactory.

The word "differentiation" is advisedly and very generally used to mean the actual separation of facies which were once in mutual solution or formed parts of the same body of erupted magma. One cannot postulate initial homogeneity for every erupted magma, nor assume that any heterogeneity a magma possesses has been caused by the break-up of an initially homogeneous solution. For example, if Suess's idea, that crust rocks are fused by juvenile gas rising from the deep, hot interior of the earth, should prove correct for any eruptive center, initial heterogeneity for the new magma would not be improbable. Each part of it might become still more heterogeneous through partial crystallization or other processes, but the original heterogeneity might persist. The rock phases resulting from originally different parts of the magma would be different; they can be called differentiates only by destroying the useful definition of "differentiation" already adopted, expressly or tacitly,

by most petrologists. A similar conclusion follows if any other cause for initial heterogeneity be considered.

Secondly, the term should apply to separations in hybrid magmas, whether formed by the mixture of two or more liquids (Bunsen, Harker) or by the magmatic solution of solid rock (Cotta, many French, Scandinavian, Russian, Australian, and Canadian petrologists). Bowen himself believes in a moderate amount of assimilation. As Loewinson-Lessing has specially insisted, a small degree of contamination with foreign material may change equilibrium in the magma, which therefore separates into strongly contrasted parts. It would be a pity, if it were possible, to exclude a change of the latter kind from the list of those properly covered by the name "differentiation."

Petrologists of the future are, indeed, likely to agree that this word shall be used to denote *separation* of phases and that its definition should be kept free from any presupposition as to the *origin* of the magma which does separate into parts, liquid or solid. Accordingly the units of differentiation may belong to one or more of the following six classes:

1. Contrasted fluid phases of an initially heterogeneous magma, including parts particularly rich in volatile constituents.

2. Solid crystals (fractional crystallization).

3. Mother-liquor left after partial crystallization.

4. Non-consolute liquid fractions (liquid immiscibility).

5. Material of fused country rock, not diffused into the original magma (ultra-metamorphism in part).

6. Original magma locally charged with material dissolved from the country rock, but slowly diffusing from the source of supply (syntexis).

Many field and laboratory observations suggest the control of gravity during the separation in any of the six cases. Given moderate viscosity for the magma, most early-formed crystals should rapidly sink. The formation of these crystals commonly means a decrease of density in the adjacent liquid, which is thus made specifically lighter than the surrounding magma. Such locally generated mother-liquor should tend to rise and concentrate near the roof of the magma chamber. Differential densities must tend

to cause gravitative adjustment among the liquid parts of an originally heterogeneous magma. The parts richest in gas are likely to rise roofward, displacing gas-poor parts of otherwise similar composition. A xenolith of gneiss, melted by, but not diffused into, a moderately viscous gabbroid magma, would rise rapidly and segregate with other melted bodies of the same kind. The most fusible part of the disintegrating xenolith would rise or sink independently. Even if diffused, the more acid foreign material locally lowers the density of the magma, for diffusion is a slow process. On the other hand, the local masses of acidified gabbro will rise quickly if the viscosity of the main body of gabbro is low.

Differentiation of the units described in classes 1, 5, and 6 may take place without any crystallization whatever; that is, all the phases concerned are liquid. Yet in none of the cases is the principle of fluid immiscibility necessarily concerned. The gas, juvenile or resurgent, like the xenolithic gneiss, may be perfectly miscible with the original magma; nevertheless gravitative adjustment is compelled long before homogeneity could be produced by the diffusion of foreign matter.

Whether true liquid immiscibility is an additional, perhaps very important, factor in magmatic differentiation is uncertain. Yet the repeated dogma that this question must be answered in the negative for natural silicate solutions is not warranted. The proper answer awaits the time when the influences of undercooling (by pressure, etc.) and volatile agents, as well as other unknown conditions, are better understood than now.

Bowen has done good service in confirming the view that the diversity of igneous rocks may be partly due to the sinking (or rising) of early-formed crystals in magma, but he has carried the principle farther than it is safe to carry it in the light of present knowledge and in the dark of present ignorance. His definition of differentiation is subjective, since that process is assumed to affect only purely juvenile magma "without foreign contamination." With respect to the biggest problem in petrogeny he thus takes a position which a host of field facts renders untenable. Certain observers ascribe to magma the power to dissolve completely large percentages of country rock. Others, more cautious

in admitting assimilation on the great scale, yet believe a small amount of syntexis to be capable of upsetting equilibrium in a primitive magma and so initiate its marked differentiation. These authors are so fortified with reasons for their faith that it is clearly expedient to keep an open mind concerning syntexis and to define "differentiation" accordingly.

Absence of fractional crystallization in most basaltic sills.—Another general objection to the pure-fractionation hypothesis is that it seems to prove too much. Numberless basaltic (diabasic, gabbroid) sills show by their wide extent that they were comparatively fluent during injection. Presumably the interior portion of each sill of notable thickness remained fluent for some time (hours, days, or weeks) after injection. During this interval the magnetite, olivine, augite, or calcic plagioclase of early crystallization would sink if the basalt regularly behaved like Bowen's crucible melts, on which he so largely bases his theory. Strong differentiation through the sinking of crystals was observed in his artificial melts after these had stood only a few minutes or at most a couple of hours. If, therefore, the experimental analogy were good, the average basaltic sill, five to fifty meters thick and hence slowly chilled, should exhibit differentiation by gravity. According to Bowen's argument, diorites or even quartzose phases might be regularly expected near the roofs and ultra-femic phases near the floors.

These deductions do not match the facts; the chemical homogeneity of most basaltic sills is almost perfect. The gravitative differentiation of basaltic magma is manifestly slow and, in a sense, difficult. Very thick sills, like that of the Palisades of New Jersey, may preserve magmatic life long enough for an appreciable sinking of specifically heavy crystals toward the bottom, but in general it looks as if some "contamination" were necessary before ordinary injected basalt breaks up into contrasted phases. The "contaminating" materials may be either exotic juvenile gas or resurgent gas or liquid.

Comparative homogeneity of femic phases in differentiated sills and laccoliths.—Where gravitative differentiation has taken place in sill or laccolith, the femic phase is commonly rather uniform from top to bottom, except at the layer transitional to the over-

lying, more salic phase. For example, the lower four-fifths of the Pigeon Point sill on the shore of Lake Superior is made up of gabbro. Locally the gabbro does bear interstitial micropegmatite, but from below upward there is no regular increase in this more siliceous ingredient. Such increase is rapid in the thin, overlying, intermediate rock, which is in turn overlain by the thicker, nearly homogeneous roof phase, micropegmatitic granite or red rock. According to the theory under discussion, the quartzose red rock represents the last surviving liquid of basaltic magma from which a correspondingly *large* crop of femic crystals had settled out. At some level between roof and floor these should be specially concentrated. Yet nowhere in the sill is there any important concentration of olivine, pyroxene, or iron oxides beyond the amounts characterizing a normal gabbro. The hypothetical ultra-femic phase is missing, despite the field evidence that the original magma was a rather typical gabbro.[1]

The same is true for at least some of the magnificent sills of the Purcell Mountains, also studied by the writer.

Incidentally, the cooling of a sill undergoing fractional crystallization is seen to be no simple matter. During the formation of a solid crystal, latent heat, estimated as about one-fifth of its total melting-heat, is given off. The fall of magmatic temperature at the level of its growth thus tends to be retarded. The deeper levels to which the crystal sinks share practically none of this latent heat in a direct way. Apart from other causes, the lower layers of the sill magma should therefore freeze first. The level of maximum aggregation of sunken crystals cannot be readily foretold, though it must be above the quickly chilled floor phase of the intrusive.

Origin of the pre-Cambrian granites.—Bowen considers all granite to be a differentiate of basaltic magma. Most of the continental surfaces are apparently underlain by pre-Cambrian complexes, chiefly of granitic composition, though so often metamorphosed to gneiss. If these stupendous masses of granite represent the silicic pole of separation in original basalt, most of the continents must now be underlain, still deeper than the granites, by solid rock much more femic than basalt and of great aggregate volume. Or

[1] Cf. R. A. Daly, *Amer. Jour. Sci.*, XLIII (1917), 423.

else the immense crops of olivine, pyroxene, magnetite, etc., were dissolved in still deeper, very hot magma which may still be liquid. If it is this magma that has been erupted in post-Cambrian time as basalt, then the original magma was not typically basaltic but more salic. On the other hand, there is no field evidence of the assumed generation of ultra-femic differentiates below the pre-Cambrian granite terranes, even if some special mechanism existed whereby the sunken crystals of this early differentiation were arrested at levels above the source or sources of the primitive basalt. Since peridotites, most probably derived from the relatively small volumes of basaltic magma involved in post-Cambrian igneous activity, have been erupted from time to time, it is reasonable to suppose that much more numerous and larger bodies of peridotites should have been erupted during the pre-Cambrian, if the pre-Cambrian granites were differentiated from basalt. The fact is that peridotites are by no means conspicuous in the pre-Cambrian complexes.

As noted elsewhere, the writer is more disposed to regard the basalt of the world as itself a primeval differentiate, the sunken part of an intermediate magma, of which the other risen part is the material now constituting the granitic terranes of the pre-Cambrian.[1]

Rapid transitions between phases of differentiated injections.—Though in each differentiated sill or laccolith the salic and femic phases are generally separated by a layer of rock chemically intermediate between the two, this layer is often very thin. Thus, at Square Butte, Montana, the transitional rock between the syenite and shonkinite of the well-known laccolith is only "a few inches or a foot or so" in thickness. Pirsson describes the transition as "extremely abrupt."[2] Considering the large scale of this differentiation and remembering the distribution of the sunken crystals in Bowen's experiments, such abruptness of transition is hardly to be expected if the differentiation were due merely to fractional

[1] From Bowen's account of the evolution (p. 40) it is not easy to see how the potash of basalt could be concentrated in the proportion seen in granite, assumed to represent the residual liquid of an initially basaltic magma, unless the soda of the granite were much more abundant than the potash; yet in average granite potash dominates over soda.

[2] L. V. Pirsson, *Bull. 237, U.S. Geol. Surv.*, 1905, p. 51.

crystallization.[1] Nor here again does the hypothesis explain the comparative homogeneity of the shonkinite itself.

Origin of quartz diabase.—A difficulty is found also in the nature of that common sill rock, quartz diabase. Table I gives the average composition of twelve typical quartz diabases from various parts of the world (col. 1) and the average analysis of 198 fresh rocks of basaltic composition (col. 2), each average being reduced to 100 per cent.

TABLE I

	1	2
SiO_2	52.34	49.06
TiO_2	1.82	1.36
Al_2O_3	13.70	15.70
Fe_2O_3	5.05	5.38
FeO	8.78	6.37
MnO	0.23	0.31
MgO	4.72	6.17
CaO	8.03	8.95
Na_2O	2.60	3.11
K_2O	1.17	1.52
H_2O	1.56	1.62
P_2O_5	....	0.45
	100.00	100.00

Typical basalt, like normal diabase, contains no quartz. The quartz diabases mentioned carry 4 per cent to about 20 per cent of that mineral, and varying proportions of biotite, from zero to perhaps 10 per cent. According to Bowen (p. 46) the quartz and biotite have crystallized because the residual liquid, from which pyroxene, calcic plagioclase, and possibly olivine had settled out, became "enriched in alkaline feldspar molecules and water to give a high concentration and consequent separation of most of those molecules which are formed by the breakdown of the alkaline feldspar molecules (biotite or quartz or both)." But the high content of lime and magnesia in quartz diabase shows the amount of sunken pyroxene, olivine, and plagioclase to be very small. In fact, Collins has illustrated quantitatively the fact that much quartz diabase is essentially normal diabase bearing interstitial

[1] Cf. N. L. Bowen, *Amer. Jour. Sci.*, XXXIX (1915), 178 ff.

micro-pegmatite or myrmekite.[1] On the other hand, quartz diabase is characteristically poorer in alkalies than normal diabase or basalt—a relation just the reverse of that expected on Bowen's hypothesis.[2]

Hence, neither the mineralogical constitution of quartz diabase nor its chemical analyses support the idea that its free quartz is due to fractional crystallization, as postulated.

Gas-controlled differentiation in the liquid phase.—That fractional crystallization is only one of several important modes of differentiation is suggested by the activities of magmatic gases. All petrologists recognize the segregation of gas-rich, generally salic, material as magmas complete their crystallization. Assuredly the gases of mobile fractions have been concentrated by the formation of gas-poor, solid crystals. However, one cannot assume a total absence of gas-rich portions in the original magma nor a total inability of resurgent gases to enter the magmatic chamber. If, for these or other reasons, local portions of the magma are or become specially gaseous, these would tend to rise in the chamber and so bring about differentiation independently of crystallization and, it may be, long before crystallization has begun.

The writer has emphasized the possible derivation of augite andesite from basalt by the sinking of crystals. The abundant gas which streams through the vents where augite andesite is generated doubtless lowers the temperature range of consolidation and thereby lengthens the time interval during which crystals may settle. It may also act as a vehicle for the moderate concentration of silica and alkalies in the pipes and thus accelerate the development of a magma contrasted with the original basalt.[3] Lawson expressed a somewhat similar idea in discussing the more salic central parts of the differentiated diabasic dikes around Rainy Lake.[4] This conception does not necessarily imply any degree of immiscibility between the gas-rich and the gas-poor phases of the liquid. It is

[1] W. H. Collins, *Memoir 95, Geol. Surv. Can.*, 1917, p. 96.

[2] See R. A. Daly, *Igneous Rocks and Their Origin* (New York, 1914), p. 321.

[3] Cf. R. A. Daly, *ibid.*, p. 377. That anorthositic differentiation takes place under contrasted conditions is noted on p. 328 of the same book.

[4] A. C. Lawson, *Amer. Geol.*, March, 1891, p. 160.

founded on the slowness of diffusion, a process so sluggish that homogeneity cannot be established or re-established before those phases have been separated by gravity or other forces.

Question of liquid immiscibility.—Bowen decides against the hypothesis of liquid immiscibility as a condition for the splitting of silicate fractions. His chief reason is the negative evidence of experimental melts and of glassy lavas; in neither case have immiscible globules been detected, though the artificial or natural quenchings have taken place at all stages in the cooling histories. In spite of such observations, even on melts "in bombs under high pressure of water-vapor," one cannot but question whether melt or lava flow truly represents the controlling conditions in a great, *quiet*, magma chamber. There, at pressures of hundreds or thousands of atmospheres, the magmatic life is to be measured in weeks, months, years, or centuries. Bridgman's work indicates the probability of the great undercooling of such a magma by pressure. Kuenen has proved that for some liquids pressure raises the critical temperature of unmixing, for other liquids the reverse.[1] Is immiscibility among silicate solutions developed by undercooling through pressure? Further, are the possibilities of the colloidal state for silicates at continued high pressure sufficiently understood? Until these and kindred problems are solved a definite denial of liquid unmixing in magmas should be postponed.

Bowen's second reason for rejecting that principle is found in the high melting temperatures of olivine, magnetite, and other components of monomineralic rocks. Temperatures so high cannot be easily, if at all, assumed for most magmas. Yet it is not ascertained that the phase which has separated was pure olivine, magnetite, or any other of the minerals forming the actual monomineralic mass. The temporary dissolving of a very small proportion of hydrogen, oxygen, or water in any of these substances gives the solution a lower temperature of consolidation than that of the corresponding gas-free phase. The writer has long realized the difficulty of crediting all the observed serpentinization of dunites

[1] P. W. Bridgman, *Proc. Amer. Acad. Arts and Sciences*, XLVII (1912), 530; *Physical Review*, III (1914), 182; *ibid.*, VI (1915), 14; J. P. Kuenen, *Phil. Mag.*, VI (1903), 637.

to ordinary weathering or to the action of seepage waters. Possibly much of the alteration is due to magmatic water. Similarly the segregation of the Kiruna magnetite in a liquid phase was perhaps possible because that phase temporarily carried appreciable amounts of oxygen, water, or other gases.

Whatever values these surmises may have, neither the field relations nor the microscopical petrography of a dunite or of the Kiruna magnetite seem to be compatible with the idea that either rock type is a "raft" of accumulated crystals. The writer believes, therefore, that it is wise to keep the hypothesis of liquid unmixing as still one of the competing explanations in these two cases also.

Failure of sufficient allowance for magmatic assimilation.—The difficulty of excluding syntexis as a significant general process may be illustrated from a field where Bowen himself has worked. In 1910 he concluded that the granophyre at the roofs of several diabasic sills in the Gowganda district, Ontario, is to be referred to the solution of the invaded sediments.[1] Later he wrote:

> This opinion was arrived at principally because of the difficulty of picturing any process of pure differentiation whereby a quartzose rock could be formed from basaltic magma. With this difficulty removed the writer has no hesitation in concluding that the granophyre and the micropegmatite interstices of the diabase were formed after the manner detailed in the present paper [fractional crystallization of pure basalt] and that interchange of material between the granophyre and the adinolized sediment was a subsidiary process contributing to the soda-rich nature of the border phases.[2]

Since 1910 Collins has studied the sills of the same district in detail, proving that granophyric (micropegmatitic or myrmekitic) material has resulted from the interaction of the diabasic magma and the invaded quartzite, etc.[3] Though Collins is conservative in theorizing about the origin of the main granophyric bodies, his evidence agrees with the findings of Bayley, Lawson, and the writer at Pigeon Point, and with the first field impression of Bowen in Collins' field. In view of the close analogy between granophyre and granite the agreement is significant.

[1] N. L. Bowen, *Jour. Geol.*, XVIII (1910), 658.

[2] *Ibid.*, Suppl., XXIII (1915), 49.

[3] W. H. Collins, *op. cit.*, pp. 60, 90. See especially the remarkable photograph in Pl. VIII, *A*.

Differentiation a reversible process.—Tolerance toward the idea of assimilation ought to be specially easy for petrologists who have studied the proofs and processes of differentiation, for differentiation is reversible. This is shown in a variety of ways: First, the original formation of the unstable melt means the former existence of conditions compelling the thorough, mutual solution of all its components. The local re-establishment of those conditions would lead to the re-solution of phases once separated from the original magma. Secondly, the resorption of phenocrysts is a very common proof of re-solution and that on a large scale. The crystals forming early in artificial melts are often resorbed before equilibrium is reached. Salt and cold water saturated with salt make a stronger brine at higher temperature. Can hot, primary basalt fail to dissolve some of the heterogeneous substances of the earth's crust with which it makes contact during and after eruption? Thirdly, because the order of eruption is roughly parallel to that of crystallization, and for other reasons, the temperatures of differentiation are to be considered as relatively low. Higher temperature should, then, presumably tend to restore homogeneity. Finally, the solution of older gabbro in the red-rock magmas, shown at Pigeon Point, Duluth, near Nordingrå, and elsewhere, proves the ability of even a late differentiate to make a new mutual solution with solid rock of essentially the same kind as that now representing the other pole of its own differentiation.[1]

If, then, magmatic differentiation is reversible, assimilation of foreign, solid rocks is seen to be all the more probable. The case of the red rock and gabbro shows that very high temperature may not be necessary for solution; concentration of water is another of the important factors.

Space cannot here be taken for a statement of the many facts (e.g., replacement of invaded formations by batholithic rocks) directly supporting the assimilation theory. They are amply competent to forbid belief that fractional crystallization is the only important cause for the diversity of igneous rocks. Some revision of the subject is called for when Bowen (p. 90) remarks that the

[1] R. A. Daly, *Amer. Jour. Sci.*, XLIII (1917), 442 (footnote); A. G. Högbom, *Geol. Fören. Stockholm Förhand.*, XXXI (1909), 368.

reasons for assuming assimilation on an appreciable scale "are considered to be *entirely* removed when it is shown that the types enumerated above and probably all other igneous rocks *could* be derived from basaltic magma by differentiation alone." A lapse of logic is indicated by the italicized words.

Hybrid rock not the normal result of assimilation.—One must doubt that the "formation of an obviously hybrid rock" should be the "normal result of assimilation" (Bowen, p. 85). A fused xenolith or the solute slowly diffusing away from its source into the dissolving magma tends, as already noted, to rise (or sink) in the general body of liquid. As the foreign material moves under gravity it is more and more mixed with the original magma. This more dilute solution, retaining nearly all of its original temperature, is about as likely to separate as any part of the original magma itself. The special composition of the absorbed rock may of itself stimulate strong differentiation. Under the conditions hybridism is far from being obvious.

The lowering of crystallization temperature by mixture may have little to do with the differentiation of many syntectics. Back of all theorizing are two fundamental questions: How greatly is primary, dissolving magma superheated? What is the ratio of its volume to that of its solute? In other words, how much work is supposed to have been done and what was the amount of energy available?

The petrologist should think always to scale, in space!

Meaning of chilled contacts in batholiths.—Bowen states (p. 84) that little assimilation can be admitted in the case where a batholith has a chilled contact against its country rock. If stoping established the visible contact, the magma was nearly frozen; for, if it had been very hot, further stoping would have occurred. The visible contact was made after the sinking away of the last batch of shattered blocks from the main country rock. The chilling effect is thus due to the relatively low temperature of the new, last surface of contact made with the invaded formation. In that case the chilling phenomena give no trustworthy indication of the assimilating power of the batholith during its enormously long magmatic life.

The petrologist should think always to scale, in time!

Loci of magmatic assimilation.—Again, the importance of batholithic assimilation is to be properly gauged only if all its different loci are kept in mind. In part it is marginal, affecting the roof region and also the vast walls, independently hot, at great depth. For the rest it consists of the fusion or solution of xenoliths, either near the roof or at deep levels. Accordingly batholithic assimilation may be described as:

1. Marginal: (*a*) High-level, (*b*) Abyssal.
2. Xenolithic: (*a*) High-level, (*b*) Abyssal.

Of the four kinds the xenolithic-abyssal and the marginal-abyssal are probably most important. Yet precisely these loci of the geological work, typically very deep, can seldom or never be exposed to view by erosion. Hence batholithic syntexis, beside which all other is an almost vanishing quantity, can be inferred only from its results. Its whole meaning for petrology is not to be directly deduced from visible contacts.

Bowen's special suggestions as to the origin of alkaline types.—The foregoing considerations are vital in the theory of alkaline rocks, but Bowen's petrogenic scheme raises doubts when some of his more specific points are examined. He recognizes two principal modes of origin for the alkaline rocks, as stated in the following quotations from his memoir (pp. 56, 57):

It has been shown that at the biotite granite stage [of evolving basaltic magma], and to a lesser extent in preceding stages, reactions take place in the liquid whose principal feature is the breakdown of polysilicate molecules, probably under the influence of water, to the simpler orthosilicate molecules, among them $KAlSiO_4$ and $NaAlSiO_4$. The precipitation of $KAlSi_3O_8$, $NaASi_3O_8$, $KAlSiO_4$ in mica, and SiO_2 as quartz means the concentration in the liquid of all the other molecules indicated in the reactions given on pp. 44 and 45. These are principally $NaAlSiO_4$ and the volatile constituents, water, chlorine, etc., with their compounds. If the crystals of the biotite granite stage, including quartz, sink out of this liquid, then the concentration of $NaAlSiO_4$ will finally reach a stage where nephelite will begin to precipitate. There may also result a concentration of CO_2, S, SO_3, Cl, etc., sufficient to cause their precipitation in compounds such as cancrinite, lazurite, hauynite, and sodalite, minerals which are peculiar to nephelite syenites and related rocks. . . . .

Differentiation during crystallization from these very fluid [alkaline] magmas will take place very freely, and the formation of both highly femic and highly alkalic types (rich in feldspathoids) may result. The more "basic"

types of alkaline rocks are not, however, in all cases basic differentiates from nephelite syenite magma. The reactions preliminary to the separation of quartz and biotite begin at an early stage in the crystallization of basaltic magma, and the separation of these minerals may take place at an early stage, giving rise to quartz diorites or granodiorites. The possibility of the formation of alkalic magma at a stage much earlier than the biotite granite stage is thereby introduced if conditions are favorable. Favorable conditions seem to consist in the opportunity for sinking, not only of the plagioclase crystals and femic minerals, but also of the quartz crystals in sufficient amount. Thus may result relatively "basic" alkaline magmas from which such rocks as basanite might be formed, and nephelite syenite itself as a light differentiate.

Assumed desilication by the settling-out of quartz crystals.—The evolution of feldspathoid-bearing magma from the biotite-granite stage is supposed to be accomplished by the separation of crystals of orthoclase, albite, mica, and quartz. A critical element is the actual removal of quartz, and the doubtful nature of this assumption affects the whole argument. In frozen granite, whether a part of a large batholith or wholly constituting a more quickly chilled sill or dike, the quartz is all, or nearly all, interstitial. In the typical case there is no evidence that the quartz crystallized early, so as to be capable of settling-out. Rhyolites do bear phenocrystic quartz, but probably for special reasons. It would be wrong to regard rhyolites as exact homologues to granite in mode of crystallization. In any case the groundmass of rhyolite or quartz porphyry is itself very rich in free silica, and it is difficult to imagine how the groundmass quartz could be removed so as to leave a quartz-free residuum like nephelite syenite.

The same trouble arises in connection with the second postulated method of development, namely, from quartz-diorite or granodiorite magma. The quartz of quartz-diorite and granodiorite is again interstitial and seldom shows any tendency to phenocrystic relations.

Origin of basanite.—Can basanite be derived by the sinking of quartz and other minerals from evolving basalt? Solid basanite has a specific gravity near 2.95. In the liquid state its specific gravity would be about 2.60, a value little if any greater than that of the magma in the immediately preceding stage. On the other hand, the quartz crystals at the temperature of this magma would

have a specific gravity of about 2.54. Obviously the assumption that they would sink at all needs further justification.

The hypothesis concerned faces objections on chemical grounds. Table II gives the average of the analyses of 20 typical basanites (col. 1) and the corresponding averages for 20 quartz diorites (col. 2) and 12 granodiorites (col. 3).

TABLE II

	1	2	3
SiO_2	44.41	59.47	65.10
TiO_2	1.56	0.64	0.54
Al_2O_3	15.81	16.52	15.82
Fe_2O_3	4.66	2.63	1.64
FeO	5.85	4.11	2.66
MnO	0.14	0.08	0.05
MgO	8.20	3.75	2.17
CaO	10.12	6.24	4.66
Na_2O	3.81	2.98	3.82
K_2O	2.37	1.93	2.29
H_2O	2.42	1.39	1.09
P_2O_5	0.65	0.26	0.16
	100.00	100.00	100.00

Inspection of the table shows that the settling-out of "plagioclase crystals and femic minerals" as well as quartz could not produce a basanitic magma from that of either quartz diorite or granodiorite. For instance, the potash should be much higher in the basanite unless it be assumed that much biotite had settled out; but if it had, the iron oxides and magnesia should be proportionately diminished. Yet these components of the femic minerals are much more abundant than in either of the postulated parent magmas. Nor is it likely that the lime could be relatively so much increased in the mother-liquor after the manner suggested, that is, by the sinking (or rising) of plagioclase crystals and femic crystals.

Absence of foyaitic types in most batholiths and stocks.—Again the theory suffers statistically as regards the occurrence of alkaline rocks. If, as Bowen holds, the cooling of a great body of granite magma should normally generate a foyaitic submagma as an end product, then all or most granite batholiths and most of the largest stocks should exhibit foyaitic phases. They do not.

Absence of quartz-bearing lavas in many basalt-trachyte-phonolite volcanoes.—Similarly phonolite should emanate from most old, large volcanoes. Quartzose lavas (quenched, interim phases) should be commonly found in the oceanic volcanoes which are built of phonolite or trachyte and basalt. These expectations also do not agree with the facts.

Eruptive sequence.—In view of the great complexity of the problem not too much stress should be laid on special cases, but it is well to point out a questionable argument relating to the eruptive sequence. Bowen implies (p. 64) that the nephelite syenite-malignite member of the Okanagan composite batholith has its theoretically correct time relation to the other members. On the contrary, the alkaline body is distinctly older than the Similkameen granite batholith, and not younger, as would be naturally expected if the alkaline mass represents the residual liquor of the granite as it crystallized. The neighboring, intensely sheared Osoyoos granodiorite is very much older than the unsheared alkalines, and any direct genetic bond between these two is improbable.

More generally, the writer cannot believe that the world's eruptive sequences support the thesis that foyaites, phonolites, trachytes, etc., are simply the products of the fractionation of pure basalt.

Comparison of basalt and femic, feldspathoid-bearing types.—A formidable array of difficulties with that explanation appears when average basalt (see col. 1 of Table III) is compared chemically with the more femic members of the alkaline suite, such as average nephelite basalt (col. 2), analcite basalt from the Highwood Mountains (col. 3), average leucite basalt (col. 4), average leucite basanite (col. 5), and average theralite (col. 6).[1]

The high lime, magnesia, and iron oxides in cols. 2 to 6 inclusive cannot be reconciled with the hypothesis that the relatively high soda or potash has been developed by the removal of olivine, pyroxene, or calcic plagioclase, or any combination of them, out of an average or typical basaltic magma. The lime content of

[1] Cf. Table II in the writer's *Igneous Rocks and Their Origin*, 1914; and L. V. Pirsson, *op. cit.*, p. 173.

cols. 2, 4, and 5 and the high magnesia of col. 2 are specially noteworthy. On the other hand, this hypothesis does not explain the dominance of potash over soda in cols. 4 and 5, nor the abundant water in the analcite basalt.

TABLE III

	1	2	3	4	5	6
SiO_2	49.06	39.87	47.82	46.47	45.34	45.61
TiO_2	1.36	1.50	0.67	1.33	1.30	1.96
Al_2O_3	15.70	13.58	13.56	15.97	16.59	14.35
Fe_2O_3	5.38	6.71	4.73	5.97	5.83	6.17
FeO	6.37	6.43	4.54	4.27	4.76	4.03
MnO	0.31	0.21	tr.	0.01	0.01	0.19
MgO	6.17	10.46	7.49	5.87	5.43	6.05
CaO	8.95	12.36	8.91	10.54	11.64	9.49
Na_2O	3.11	3.85	4.37	1.69	2.93	5.12
K_2O	1.52	1.87	3.23	4.83	4.55	3.69
H_2O	1.62	2.22*	3.37	2.32	1.12	2.60
P_2O_5	0.45	0.94	1.10	0.73	0.50	0.74
	100.00	100.00	99.79	100.00	100.00	100.00

*Includes 0.29 per cent CO_2.

Perhaps fuller statement of the hypothesis might annul some of the writer's doubts which have been raised by these and other fundamental facts of magmatic differentiation, but at present he fails to see that the mechanism works as it should if the pure-fractionation theory were correct.

Admission of some assimilation by magmas.—Bowen states (pp. 84, 89):

> As a matter of fact, plain evidence is found in the field that magmas do assimilate, especially when they occur in the large bodies commonly termed batholiths. . . . . It may well be, also, that some melilite rocks are formed by the crystallization of a syntectic magma formed by the solution of limestone. . . . . If the absorption of any considerable amount of limestone by a magma can be admitted, it may be expected to have a very unusual effect upon the magma. . . . . The taking of silica from feldspar molecules by the lime and the consequent production of feldspathoid molecules might well be supposed a reasonable possibility. Some alkaline rocks may, perhaps, be so generated.

Yet Bowen believes "that normally the alkaline rocks enter into an eruptive sequence as the products of differentiation solely."

Only a very small addition of foreign lime (1 to 10 per cent) to a large mass of basaltic magma would be necessary to produce

the total amount of desilication observed in any nephelitic or leucitic body yet discovered. Considering the fluxing power of limestone or dolomite on silicate melts, such moderate, local assimilation is surely not improbable. More siliceous sediments or even gneissic or granitic rocks may be simultaneously dissolved; but, on account of its character as a flux, a carbonate rock is likely to be absorbed in greater volume. Hence it does not follow that the solution of "an occasional bed of limestone in a terrane consisting principally of siliceous gneisses . . . . would entail simultaneous absorption of a much greater quantity of relatively siliceous material" (Bowen, p. 63). The relative amounts absorbed must really depend on a number of factors, including the contact relations of each layer of the country rocks to the invading magma.

Meaning of melilitic rocks.—Bowen's admission regarding the melilite rocks is of particular significance when one remembers the exceeding intimacy of alkali-rich rocks with melilite basalt, nephelite-melilite basalt, and alnöite.[1]

Résumé.—The prominent difficulties with Bowen's theory may now be summarized.

The sinking or rising of crystals in magmas is a true cause of diversity in igneous rocks, but it is not the only important cause; perhaps it is much less important than the separation of liquid phases. Apart from the possible development of "liquid immiscibility" in an initially homogeneous magma, separation in the liquid phase is to be expected: (1) if the magma at the time of emplacement in a large chamber were heterogeneous; (2) if for any reason gases are concentrated locally within the magmatic body; and (3) if the assimilation of country rocks, or of their volatile constituents alone, takes place. The field evidences for important assimilation are not consonant with the pure-fractionation theory.

Bowen's theory seems to imply a greater facility of differentiation for basaltic and other magmas than they actually possess; most sills and laccoliths are not visibly differentiated, even though they show features implying fluency after injection. The theory gives no good explanation of the comparatively abrupt transition

[1] See the writer's *Igneous Rocks and Their Origin*, p. 436, and Appendix D.

between the syenite and shonkinite of the Square Butte laccolith, nor of the apparent homogeneity of that shonkinite. It fails to take account of the lack of ultra-femic phases in the Pigeon Point and other sills which display notable salic differentiates. Its consequence, that all monomineralic rocks except certain sulphides are crystal "rafts," may fit the case of anorthosite, but not other cases. Other special objections are found in the chemical nature of quartz diabase, basanite, and the "alkaline basalts." The absence of foyaitic phases in, or apophysal from, most large bodies of granite, granodiorite, and quartz diorite does not agree with the theory as developed. Similarly quartzose lavas, expected on the theory, are not found in many volcanic piles containing trachyte or phonolite with basalt. The lack of quartzose lavas in the enormous and therefore long-lived volcanoes distributed over the main ocean floor is a fact not easily explained by the theory.

Bowen has given the clearest, most detailed argument for the significance of fractional crystallization which has yet been published. His general theory takes cognizance of: the proved genetic association of alkaline rocks with subalkaline magmas, especially the basaltic; the small size of alkaline bodies; their richness in gases and rare elements; the consequent effects regarding grain and variability of composition; the roof positions of alkaline differentiates in many sills, laccoliths, and batholiths; and the concentration of alkalies. Nevertheless, all of these facts are explicable also on the syntectic-differentiation hypothesis, which does not encounter certain difficulties facing the theory of pure fractional crystallization.

GENERAL CONCLUSION

Thus the study of the geological publications issued since the completion of the manuscript of the writer's *Igneous Rocks and Their Origin* has led him to renewed faith in the general explanation there advanced for most of the alkaline rocks. Several expert field observers have sympathetically entertained the hypothesis of control by the syntexis of basic sediments charged with volatile matter. Evidence for the derivation of alkaline rocks from subalkaline magmas has been still further accumulated. Some authors have expressed a degree of confidence that basalt is the only primary

magma eruptible since the end of pre-Cambrian time. Foye has made an extraordinarily important contribution in showing the vast quantity of alkaline solutions which may emanate from granite invading a limestone terrane. Like Allan he has given new, good evidence of the influence of gravity in the separation of magmatic phases. Foye corroborates the decision of Adams and Barlow as to the syntexis of limestone and granite in a complex now famous for its nephelite syenites. Quensel's discovery of an analogy to Alnö in the Almunge district and of the peculiar abundance of vesuvianite in the Almunge canadite is likewise to be particularly recorded. The arguments presented by Cross, Marshall, Richards, and others against the sediment-syntectic explanation of the alkaline rocks are seen to be inconclusive.

Shand finds the syntexis of limestone a partial explanation of undersaturation in igneous rocks. Smyth's view concerning the alkaline series is not acceptable, on the ground that he fails to show cause for the local and exceptional assembling of alkaline elements from subalkaline magmas, assumed by him to be purely juvenile. Experiments by Ross and other students of the commercial-potash problem show the power of lime to volatilize the alkalies from feldspathic or clay mixtures, even at comparatively low temperature.

Certain aspects of Bowen's comprehensive theory have been studied. Serious doubt adheres to some of his fundamental postulates, summoned to explain the descent of alkali-rich rocks from subalkaline magma. On the other hand, many features of his excellent paper must receive hearty commendation from all thinking petrologists; in masterly fashion he has indicated many new, important lines of thought and research.

CONDITIONS OF DEPOSITION ON THE CONTINENTAL SHELF AND SLOPE

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CONTENTS

INTRODUCTION

Undoubtedly deposition of sediment has gone on around the margins of the continents in all ages, forming thick accumulations which have encroached upon the ocean basins. To what extent such marginal accumulations have been later uplifted and thus added to the continents may be a matter for difference of opinion; but, though in some parts of the world the sedimentary rocks represent mainly deposits in interior epicontinental seas, there are other parts—the New Zealand area, for example—in which the nature of the rocks indicates that the sediments of which they are

formed accumulated marginally to, rather than upon, one of the continental protuberances.

The subject of marginal sedimentation is closely connected with considerations as to the form and origin of the continental shelf. While this is recognized by geologists and implied by many in their writings it is not usually explicitly stated.

OPINIONS AS TO THE MODE OF FORMATION OF THE CONTINENTAL SHELF

There is a very striking contrast normally present between the gentle slope of the continental shelf and the relatively steep descent, known as the continental slope, from the edge of the shelf to the depths of the ocean. In textbooks this is pointed out, but an explanation of it is generally avoided.

Lake,[1] however, has included a discussion of the problem. In Lake's textbook and in a recent paper by Gardiner[2] several hypotheses bearing on the subject are formulated. From both the reader receives the impression that, if a hypothesis of glacial deposition be put aside as of local application, there remain in the field to account for the continental shelf in low latitudes two rival hypotheses or groups of hypotheses behind each of which there is an equal weight of authority—namely, a hypothesis of erosion with or without subsidence of the eroded surface, and a hypothesis of accumulation according to which the shelf has grown owing to deposition of sediment. It is clear, however, that both these writers favor the hypothesis of accumulation and regard the shelf as for the most part a built feature.

The acceptance of this view is the basis of many geological writings, such, for example, as an article by Chamberlin on "The Ulterior Basis of Time Divisions . . . . ,"[3] in which it is taken as axiomatic that the shelf is formed partly by cutting but mainly by deposition. The same point of view is implied by the use of such terms as "continental delta" by Gulliver,[4] signifying conti-

[1] P. Lake, *Physical Geography* (Cambridge, 1915).

[2] J. Stanley Gardiner, "Submarine Slopes," *Geog. Jour.*, XLV (1915), 202–19.

[3] T. C. Chamberlin, *Jour. Geol.*, VI (1898), 449–62; also Editorial, pp. 424–26.

[4] F. P. Gulliver, "Shoreline Topography," *Proc. Amer. Acad. Arts and Sci.*, XXXIV (1899), 176.

nental shelf, "built terrace" by Gilbert and others, and "topset," "foreset," and "bottom-set beds" by Chamberlin,[1] who thus establishes the analogy of the continental shelf with deltas.

Some clear statements have been made as to the origin of that portion of the continental shelf fringing eastern North America. Willis writes as follows:

> The plateau is composed of sands which are indeed fine near the eastern edge, yet are distinctly granular and incoherent. But soundings on the steep slope beyond the 100-fathom line have brought up very fine silt from the bank of which that slope is the surface, and this silt passes at its foot into globigerina ooze. The zone of transition from clean sand to silt is as sharp as the edge of the slope and is coincident with it. It is evident that the suspended mud which escapes beyond the estuaries and sounds of the littoral is swept out until the undertow expands over the edge of the escarpment, and is diffused in deep water; there the silt forms a great bank 10,000 feet high, with a slope of 3 to 8 degrees, which has grown seaward during geological ages, and continues to expand as erosion continues on the land.
>
> The structure of this deposit can only be inferred, but it is worthy of consideration. The surface of accumulation, to which bedding planes are probably parallel, is inclined at a considerable angle, and traverse the bank from top to bottom obliquely to the vertical thickness. The direction of the growth is outward, not upward. The conditions of deposition are similar to those of a delta advancing into fresh water, and the structure of the deposits is probably similar to that shown by Gilbert for a fresh water delta.[2]

The generalization by the same writer that "the ocean basins are now somewhat overfull . . . . not large enough to hold all the waters, which therefore extend over the margins of the continents,"[3] does not necessarily contradict the foregoing; but it omits to state that, though the growth may now be outward only, during the postulated overflow of the oceanic waters the shelf must have maintained itself by upward growth.

Barrell, also, writes as follows:

> Ocean waves are known to have a perceptible effect to a depth of about 100 fathoms, planing away the shore and the higher parts of the bottom, carrying the products of fluviatile and marine erosion outward to deep water.

[1] T. C. Chamberlin, "Diastrophism and the Formative Processes. VI. Foreset Beds and Slope Deposits," *Jour. Geol.*, XXII (1914), 268–74.

[2] B. Willis, "Conditions of Sedimentary Deposition," *Jour. Geol.*, I (1893), 497–98.

[3] B. Willis, "Principles of Paleogeography," *Science*, N.S., XXXI (1910), 241–60 (see p. 244).

The waves move material along the bottom and prevent the settling of the finest silt until the limit of wave action is reached. Beyond that limit the bulk of the material is rapidly deposited from suspension. In protected situations this depth becomes less and in many places is not over fifty fathoms. There is thus built outwards around the continents a subaqueous terrace, its top gently sloping to a depth of 100 fathoms or less, its front much steeper in comparison, and giving sharpness to the continental margin.[1]

Unqualified support of any hypothesis which assigns the formation of the shelf entirely to erosion is rarely met with. In an explanation of the shelf given by Mill,[2] however, marine erosion with stationary sea-level is given first place, and even in an American textbook submergence of a plain "worn to low relief" is the only explicit explanation given.[3] That this statement does not really express this author's view is shown, however, by the following passage, which appears on another page in an explanation of coastal plains (p. 508): "Off the eastern coast of United States there is a level sea-bottom plain, known as the *continental shelf*. . . . . If there should be an uplift of 600 feet, this very level plain would be added to the continent. . . . . It would be underlain by unconsolidated sediments."

The following clear statement on the subject by Gilbert and Brigham is also worthy of attention as an emphatic refusal of support to the hypothesis of submergence of a plain of erosion:

It will be remembered that the resemblance of Chesapeake Bay to a branching river was explained by saying that the Coastal Plain had sunk down so as to let the sea flow into the Susquehanna Valley. Because we now point out that the plain is an old sea-bed which has risen, it must not be thought that one fact contradicts the other. Both changes have taken place, but at different times. After the plain had been formed under the sea it was lifted so high that rivers dug deep valleys across it; then it was lowered part way, to the present height.[4]

A somewhat similar statement from Chamberlin and Salisbury may be quoted: "Almost nowhere does the real edge of the con-

[1] J. Barrell, "The Upper Devonian Delta of the Appalachian Geosyncline," *Am. Jour. Sci.*, XXXVI–XXXVII (1913–14), 249.

[2] H. R. Mill, *The Realm of Nature* (2d ed.; London, 1913), p. 219.

[3] R. S. Tarr, *College Physiography* (New York, 1914), p. 641.

[4] Gilbert and Brigham, *An Introduction to Physical Geography* (New York, 1902), p. 153.

tinent appear above the ocean. . . . . A continuous shelf almost universally borders the continents. . . . . The continent was recently so deformed that these shelves were out of water," and, on a later page: "The continental shelf . . . . may be supposed to have been built out upon the border of the sea-basin by progressive sedimentation."[1]

The meaning of all these writers is clearly that a *continental shelf*—a *constructional* feature, built of marine sediments—has been uplifted and dissected and then resubmerged.

In textbooks the statement is frequently made that the true boundary of a continent is situated at the outer edge of the continental shelf—the "continental edge" of Murray—rather than at the shore line.[2] At first sight this reads like a negation of the view that the shelf is mainly a built feature of recent growth. Such statements seem, however, generally intended merely to convey the information that, when mean slopes of the earth's surface are plotted as a hypsographic curve, there is a sharp change of average slope at the depth of the edge of the continental shelf but none at sea-level.

THE PRESENT-DAY SHELF LARGELY CONSTRUCTIONAL

Since "rival" hypotheses of *erosion,* marine and subaërial (followed by subsidence), and *deposition* have been put forward by Lake, Gardiner, and others, it is necessary to examine critically the consequences of each.

The hypothesis that marine erosion is alone responsible for the formation of the continental shelf.—Undoubtedly wave action is capable of eroding, not only at the shore line, but at considerable depths, wherever the ratio of the waste supply to the transporting power of the sea is sufficiently low to permit parts of the rock bottom to be swept clean, and where there is at the same time sufficient movement of the water to move particles of appreciable

[1] Chamberlin and Salisbury, *Geology,* III (New York, 1906), 521, 526.

[2] The shelf is described, for example, as "submerged parts of the continental protuberance" (R. D. Salisbury, *Physiography,* p. 22), and it is stated that "the area between the actual shore and the 100-fathom is regarded as belonging to the continents, though at present overflowed by the sea" (Hatch and Rastall, *The Petrology of the Sedimentary Rocks* [London, 1913], p. 11).

size across the exposed rock. This is an accepted principle. Wave motion extends, it is believed, to a depth of about 100 fathoms in the open ocean; it has been shown to be sufficiently strong to move gravel at a depth of 36 fathoms.[1] There is thus no reason to believe that, *if the bottom were kept swept clear of sediment*, erosion could not take place—though, obviously, the slowness of erosion would increase with depth—as far seaward as the edge of the shelf in 100 fathoms, at which depth there would be an abrupt change of slope from that of the shelf to that of the initial sea floor. This is the gist of the hypothesis as put forward by Mill and by Lake. The postulate of submergence following the cutting of the platform introduced by Gardiner is unnecessary.

The question arises whether clean sweeping of the cut platform such as is postulated in the preceding paragraph is possible; and it would appear that such a state of affairs must be extremely uncommon if it ever occurs. In the ordinary case deposition of the waste produced by the cutting of the platform, together with the supply from the neighboring land, must take place seaward of the area in which erosion is taking place. It is indeed obvious, as has often been pointed out, that the observed continental slope must be the surface of the last-formed layer of this sediment and represents more or less accurately the slope at which it came to rest. It seems highly probable that earlier-formed layers came to rest at the same inclination, and that some portion of the shelf is everywhere composed of such inclined layers.

The combined processes of erosion and deposition have been shown by Davis[2] and by Fenneman[3] to produce a "graded profile" or "profile of equilibrium" from the shore to the edge of the shelf, which is a fairly even slope though somewhat concave near shore and convex seaward. Fig. 1 illustrates the growth of a shelf by this combination of erosion and deposition. It will be seen that,

[1] A. R. Hunt, "Formation of Ripple Marks," *Proc. Roy. Soc.*, XXXIV (1882), 1–13 (see p. 10).

[2] W. M. Davis, "The Outline of Cape Cod," *Geographical Essays* (Boston, 1909), pp. 690–724 (see pp. 700–703).

[3] N. M. Fenneman, "The Profile of Equilibrium of the Subaqueous Shore Terrace," *Jour. Geol.*, X (1902), 1–32.

while, as the shore line recedes, erosion of the sea bottom must go on near shore, as the shelf front advances the graded profile is maintained farther seaward by deposition.

The stream of waste in transit seaward will generally, on account of its slow movement, form a thick layer on the outer part of the shelf precluding the possibility of erosion of the deeper layers of strong currents along the shelf, so that the built portion of the shelf may be narrow compared with the cut portion. In such a case erosion must extend into relatively deep water, parts of the eroded sediment or of the rock floor. It is, however, conceivable that in exceptional cases much or all of the waste may be swept away by

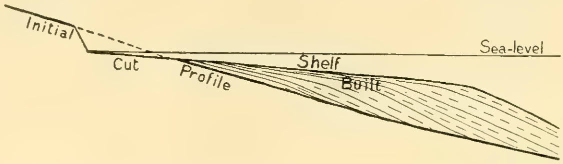

Fig. 1.—Diagram to illustrate the formation of a continental shelf by marine erosion and deposition.

floor of bedrock being occasionally swept clean. In this way are perhaps to be explained some recorded occurrences of hard bottom far out on the continental shelf.

The modification of this hypothesis which requires subsidence following marine planation has nothing to recommend it. Fig. *2a* is a copy of the figure used by Gardiner in illustration of the hypothesis, modified by the addition of a thick layer of sediment (coarsely stippled) on the top of the cut platform, which must be added to restore a normal profile. The profile of a later stage of a shelf developed by cutting and building on this initial form is also added (lightly stippled).

The hypothesis that subaërial planation followed by submergence explains the continental shelf.—In considering this possible mode of shelf formation care must be taken to exclude cases of temporary emergence of a shelf already formed. References to portions of the shelf thus temporarily uplifted, partially dissected, and again submerged have been already quoted; and oscillations of the

continental borders, if not of all land surfaces, are known to be of common occurrence.

Rapid submergence of a peneplain would undoubtedly result in the formation of a sea bottom of small relief with a general seaward slope; but it is impossible to imagine a peneplain the level surface of which would, in the period preceding submergence, end abruptly at the shore line with a sharp transition to a steep slope into the adjacent ocean basin. Even if such a state of affairs were possible, it would be necessary, in order to account for the formation of the

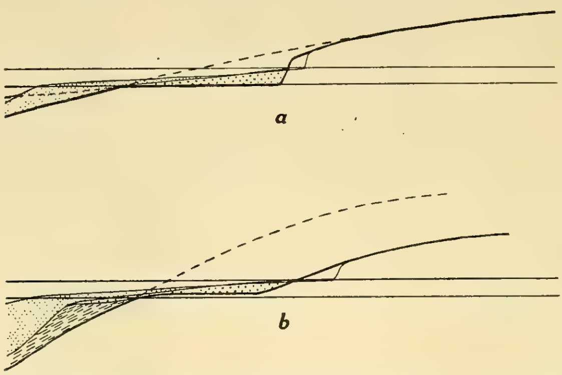

FIG. 2.—Diagrams copied from those used by Gardiner to illustrate theories of shelf formation, with additions showing the development by deposition of a profile of equilibrium.

continental shelf in this manner, to postulate a submergence of all the continental margins to the same extent, about 600 feet, and in most cases to disregard entirely the evidence afforded by the geomorphology of coastal lands as to their erosional and deformational history. A submerged peneplain could not be expected to provide, ready made, a graded subaqueous shore profile. Upon an initial surface so formed wave action would immediately come into operation, cutting in some places and depositing in others; and so, even if the initial form of any part of the continental shelf may have been a submerged peneplain, the sequential form which the shelf exhibits today must be ascribed to the work of waves.

The development of a peneplain, moreover, necessitates a very long period of erosion, during which the land mass on which it is

cut remains essentially stationary in level, and during which an enormous quantity of waste is carried to the sea. Such waste will be deposited seaward as a continental shelf of unusually great breadth, and this, when submergence of the peneplain takes place, will subside also. Since, presumably, the edge of the shelf before subsidence will be situated at or just within the 100-fathom line, after subsidence has taken place, when the width of the plain will have been added to that of the former shelf, the composite shelf so formed will extend into water much deeper than 100 fathoms. Upon such a shelf a thick layer of sediment would require to be deposited to reduce the depth at its edge to 100 fathoms; and so it appears evident that submergence of a peneplain without the subsequent co-operation of wave action on an extensive scale is not competent to produce a continental shelf of typical form.

The profiles of the shelf in the diagrams given by Gardiner to illustrate the "formation of the continental shelf by the submergence of an abrasion platform" and "of a land plain" are quite unlike those found in nature. This is perhaps intentional, as that author does not appear to favor either hypothesis. Such initial profiles would be very readily modified by wave and current action, according to the principles deduced by Fenneman.

Two stages of such modification are shown in Fig. 2*b* as an addition to Gardiner's diagram of "submergence of a land plain." The deposit added in an early stage of the modification is coarsely stippled, and that in a later stage lightly stippled.

The hypothesis that the continental shelf is formed as a result of deposition.—The conditions of delta-formation by streams bearing a load of coarse waste into lakes are now well understood chiefly owing to the work of Gilbert,[1] and an extension of the principles established by Gilbert to cover the case of rivers supplying large quantities of finer waste to the ocean has more recently been made by Barrell.[2] It is but a step from the consideration of the

[1] G. K. Gilbert, "The Topographic Features of Lake Shores," *U.S. Geol. Surv., 5th Ann. Rept.*, 1885, pp. 69–123.

[2] J. Barrell, "Criteria for the Recognition of Ancient Delta Deposits," *Bull. Geol. Soc. Am.*, XXIII (1912), 377–446.

submarine portions of deltas, which have been shown by Barrell[1] to cover often a larger area than the subaërial portions and to form large seaward protuberances of the continental shelf, to the consideration of the shelf as a whole.

Off all coasts deposition of a greater or less amount of sediment is always in progress, not only off the mouths of rivers, but along the whole length of the coast lines, and there can be a difference only in degree between such deposition and that by which the seaward, submarine portions of deltas are built forward. In the shallow water near shore conditions may be entirely different from those on the shallow-water portions of deltas; for here, as has already been shown, erosion may be going on, either deposition or erosion being in progress according to the state of balance between waste supply and transportation. Erosion near shore, however, will, generally speaking, merely have the effect of pushing the zone of deposition farther seaward.

From observation of the form and structure of the small deltas laid bare and dissected owing to the lowering of the level of the water in lakes it is known that waste, after being discharged from a river, is transported outward from the shore owing to agitation and forward movement of the water, and traverses the upper, gently sloping surface of the mass of sediment already deposited ("subaqueous plain," Barrell) until, reaching the edge, it slips over into deeper and stiller water and comes to rest at the angle of repose on the more steeply sloping front of the mass ("foreset slope," Barrell). Similarly, in the case of larger deltas of finer waste being built into the ocean, the waste is transported seaward across a subaqueous plain which is essentially a part of the continental shelf, extending outward to the depth at which the bottom is no longer sensibly stirred by wave action ("wave base," Gulliver[2]). This depth in the open ocean is clearly indicated by the

[1] *Op. cit.*, Fig. 1, p. 388; "The Strength of the Earth's Crust," *Jour. Geol.*, XXII (1914), 39–42.

[2] F. P. Gulliver, "Shoreline Topography," *Proc. Amer. Acad. Arts and Sci.*, XXXIV (1899), 176–77. As defined by Gulliver wave-base, the limiting plane toward which marine erosion will tend to lower the wave-cut platform, is "the depth to which the maximum wave action is possible." The term has been redefined by Fenneman as the depth "at which wave action ceases to stir the sediments" (N. M. Fenneman, "Lakes of Southeastern Wisconsin," *Wis. Geol. and Nat. Hist. Surv., Bull. No. 8*, 1902, p. 25).

"mud-line" of Murray and Renard, which, according to Murray, is situated at a depth of about 100 fathoms.[1] On the slope below this depth the finest particles of sediment "come permanently to rest on the bottom." Beyond the mud-line is the steeper foreset slope on which even the finest waste can come permanently to rest; but the foreset slope is much less steep and the transition to it from the subaqueous plain much more gradual than in the case of the small deltas of coarse material in lakes. For one thing water-logged mud will not remain at rest on any but very gentle slopes, and, as Barrell points out, "where, as in the case of large rivers, the detritus is mostly fine in texture, the foreset beds are built largely by material settling from suspension." The foreset beds, in which sediment swept outward along the bottom is mixed with what has settled from suspension, grade into the bottom-set beds or pelagic deposits built entirely of material settling from suspension.

In the case of portions of the continental shelf remote from the mouths of large rivers the mode of accumulation must be essentially the same as in deltas; but there will generally be present in the waste supplied from the land a much smaller proportion of the fine mud particles resulting from subaërial weathering. No doubt much of the material broken by wave attack on the shore line and supplied by smaller rivers becomes very finely comminuted in its long passage across the shelf; but the absence of a large body of mud sufficiently fine to be carried far seaward in suspension is reflected in a sharper transition from the continental shelf to the continental slope, and in a steeper inclination of the latter than is found in delta fronts. Thus the structure of the continental shelf may be regarded as presenting generally a closer resemblance to that of the subaqueous portions of small lake deltas than is shown by the corresponding portions of the deltas of great rivers.

The materials of which the shelf is being built forward are known from samples taken by oceanographers from the last layer added. These deposits on the continental slope fall into the "terrigenous" division of "deep-sea deposits, beyond 100 fathoms" in Murray and Renard's classification of marine deposits,[2] and the

[1] Sir John Murray, *The Ocean* (Home University Library), (London), p. 202.

[2] "Deep-Sea Deposits," *Report of the Scientific Results of the Exploring Voyage of H.M.S. "Challenger," 1873–76* (London, 1891); Murray, *The Ocean*, p. 201.

most common types bordering continental coasts are "blue mud" and "green mud." Examination of the samples shows that the muds have been subjected to chemical changes on the sea bottom, but that they retain their original characters sufficiently to show that the material has been derived from the land.

> As a rule they are heterogeneous from the admixture of larger or smaller rock and shell fragments. . . . . Rock fragments and mineral particles may make up as much as 75 per cent in some cases, the most characteristic species being quartz; the usual proportion of mineral particles is about one-fourth of the whole deposit. Amorphous clayey and muddy matters are always abundant, the average percentage being about 60, generally increasing in amount with greater distance from the land.[1]

Deltas and a more or less continuous shelf of typical form may be produced artificially on a small scale in a laboratory experiment, the apparatus for which has been described,[2] but, while such experiments serve admirably their purpose of illustration, it is obvious that quantitative results bearing on the relation of the depth of the edge of the shelf to wave-base would be difficult to obtain. As Davis remarks, "In most problems of geology and geography experiments have rather an illustrative than a demonstrative value."

It has often been pointed out that the edge of the continental shelf is situated everywhere (off exposed coasts) at a constant depth of about 100 fathoms, that is to say, at the greatest depth to which the water is stirred by wave action. As a matter of fact the 100-fathom line is situated generally at about the center of a convex curve to which the gentle slope of the continental shelf is tangent and which passes into the more steeply inclined surface of the continental slope. The slope begins to steepen usually from a depth of about 70 fathoms, at which depth it would seem that the effects of wave action are becoming extremely feeble.

This constant depth of the "continental edge," together with the fact that a shelf borders, with rare exceptions, all the coasts of the world whatever their origin, whether by regional uplift or subsidence, by warping or by faulting, is of great significance (see Fig. 3).

[1] Murray, *The Ocean*, p. 203.

[2] R. S. Tarr and O. D. von Engeln, "Representation of Land Forms in the Physiography Laboratory," *Journal of Geography*, VII (1908), 73–85.

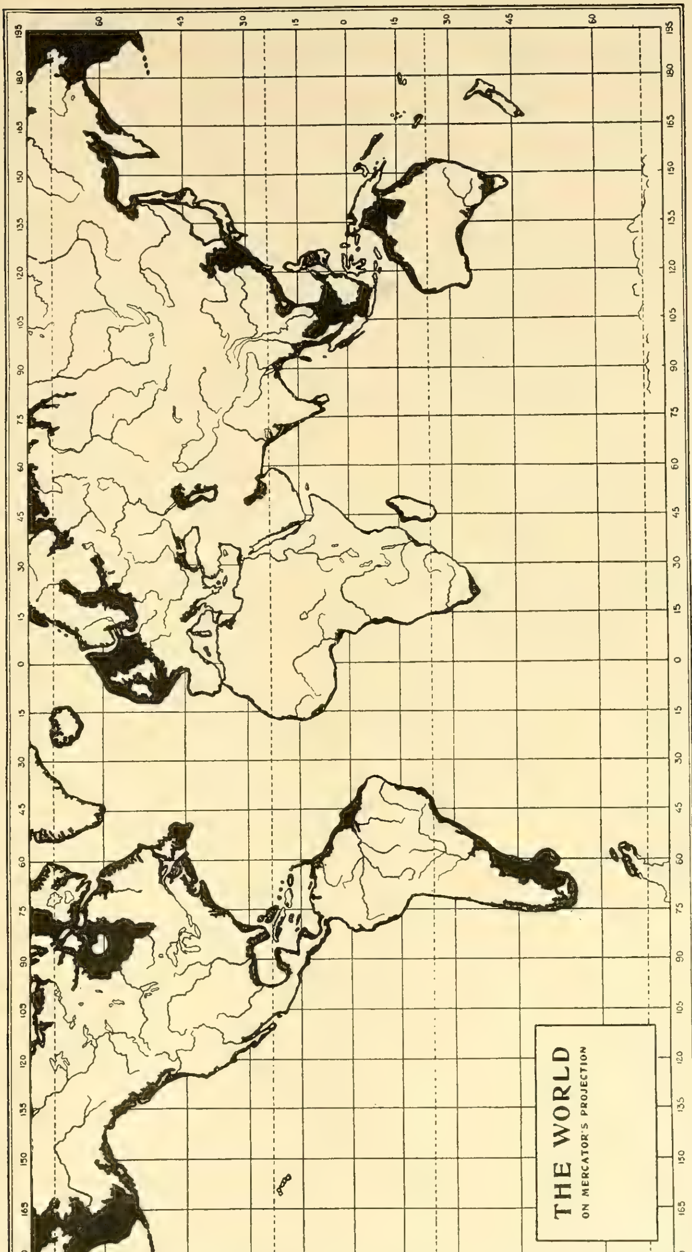

FIG. 3.—Map of the world showing the continental shelf (black)

It indicates that the present-day shelf has taken form since sea and land assumed their present relative levels,[1] and therefore that the molding of the shelf is geologically a very recent event; for most coastal lands afford evidence of considerable movements either of uplift or of subsidence having taken place at a not very distant date.

Nansen,[2] reasoning from the same data, comes to a very different conclusion. While he recognizes the practical uniformity of level of the edge of the continental shelf, he argues from the assumption that the shelf is an ancient feature and makes the remarkable deduction that, though great changes of level have taken place, which in at least some cases he regards as movements of the land rather than of the ocean, the continental margins have everywhere returned to their ancient level.

A general idea of the width of the continental shelf is given by Fig. 3. More precise data may be obtained from an inspection of ocean charts upon which the 100-fathom submarine contour line is or may be drawn, or more conveniently from the numerous maps in Stieler's atlas which show the 200-meter line. Variation in width depends on several factors; no doubt the most important is the depth of water into which the shelf has grown outward since the latest movement of the strand. If the vertical movement has been small, as, for example, around the British Isles, the present shelf is a modified older shelf, added to at the margin, and therefore broad.

Another important factor must be the presence or absence of abundant waste from the land, which will be largely determined by the presence or absence of large rivers in the vicinity. Still another must be the time that has elapsed since the latest important movement of the strand.

Variations in the width of the shelf do not affect the question of its essential continuity, which, as pointed out above, prove its capacity for rapid growth and renewal. It is obvious that the

[1] T. C. Chamberlin says of it: "The terrace is as universal (at least in its initial stages) as the sea border and is a necessary consequence of the relations of sea and land" (*Jour. Geol.*, VI [1898], 526).

[2] F. Nansen, "Oscillations of Shorelines," *Geog. Jour.*, XXVI (1905), 604–9.

shelf bordering a recently uplifted coast which has been cut back to a line of cliffs by energetic wave action must, at its landward edge, be a wave-cut platform; but even in this case farther seaward the waste derived from this retrogradation of the shore together with that brought down by rivers while cliff recession was in progress must have been deposited, forming a seaward extension of the shelf in the manner described on an earlier page. Off uplifted coasts the shore lines of which have not retreated an appreciable distance from the initial position, the shelf must be almost entirely constructional, and the same is true in the case of depressed coasts the initial embayed outline of which has not yet been much modified by marine erosion.

THE STRUCTURE OF THE BUILT SHELF

The principle is now well understood that, just as in a river the ratio of load to transporting power determines whether degradation or aggradation shall take place, so along a shore line retrogradation or progradation of the shore occurs according as the waves breaking on the shore are underloaded and hungry or are overloaded with waste from another source.

With the shore line fixed in position.—It will simplify the discussion of the structure of the built shelf if an ideal case is considered first, in which the load and the transporting power of waves and along-shore currents remain exactly balanced during the building of the shelf, so that the shore line neither retreats nor advances. Fig. 4*a* is an ideal section of a shelf built under such conditions. The front of the shelf being situated at the level of wave-base during all the stages of growth, it is clear that for each foreset bed there will be a relatively very thin topset bed, the two being different facies of the same stratum, that the topset beds will thicken seaward, and that successive topset beds will approach more and more nearly to perfect horizontality.

With the shore line advancing.—Fig. 4*b* represents the case in which the waves as they reach the shore are overloaded throughout the whole period during which the shelf is being built. The coast will be continuously prograded, and upon the growing strip of strand plain additional sand from the beach will be piled to form

dunes. The structure of the resulting shelf will be similar to that with stationary shore line with the exception that each (theoretical) foreset bed will have a subaërial as well as a subaqueous portion. In an actual case the stratification will be very irregular in the shoreward portion of the shelf, as there will be much cross-bedding in both the shallow-water and the subaërial deposits.

A very similar result is produced where the shore line advances seaward owing to the growth of an alluvial plain formed by confluent deltas, as, for example, along the coast of the Canterbury Plains, New Zealand. The structure of the whole mass of deposits,

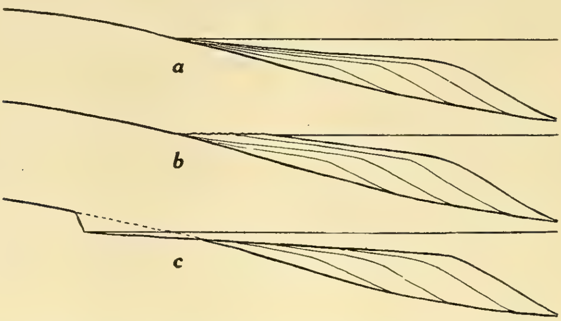

FIG. 4.—Ideal sections across the continental shelf; *a*, the shore line fixed in position; *b*, the shore line advancing; *c*, the shore line retreating.

including the alluvium of which the plain is built and the shelf which fringes it, will be similar to that of the delta of a single river as described by Barrell.

With the shore line retreating.—In Fig. 4*c* the commoner case is represented in which the waves reaching the shore have power to erode and where, therefore, retrogradation of the shore takes place (see also Fig. 1). The shelf will consist of two portions, a cut platform and a built platform, and it is obvious that the ratio of the width of the cut to that of the built platform may vary widely. As has been pointed out on an earlier page, it is theoretically possible that, in exceptional cases, there may be no built platform, the material broken by waves together with that coming from the land being swept away by along-shore currents and the shelf being entirely or almost entirely a cut platform such as that of the

Norwegian coast as interpreted by Nansen. On the other hand, owing to nearness of a large source of supply of waste from the land, the shelf may differ but little from that shown in Fig. 4*a*, there being but little retrogradation of the shore and the shelf consisting almost entirely of a built platform.

Davis, in considering the development of the graded shore profile at Cape Cod,[1] comes to the conclusion that "the critical point, where marine action changes from degrading the near-shore bottom to aggrading the off-shore bottom, migrates seaward." Clearly, however, in the general case, after a continental shelf has been developed, the direction of migration of this critical point will depend upon the relative rates of seaward growth of the shelf and landward retreat of the shore line. When the rate of growth of the built platform is rapid compared with the rate of retreat of the shore line the critical point in the profile will generally migrate landward. In this case no part of the built platform will be subsequently eroded and each topset bed will overlap the preceding one, lying upon and protecting from further erosion a strip of the cut platform. If, on the other hand, owing to rapid shore recession, the critical point migrates seaward, some of the earlier-formed topset beds will be obliquely truncated by the cut platform. While the former case is perhaps the commoner in nature, it is the latter which lends itself to diagrammatic representation, owing to the mechanical difficulty of drawing a broad shelf on a narrow page.

With the shore line alternately retreating and advancing.—The shore-line features of parts of the coast of New Zealand, notably in eastern Marlborough and western Wellington, indicate that, owing to some disturbance of the balance between load and transporting power of waves and along-shore currents, retrogradation and progradation have occurred alternately. Where such alternation is taking place, somewhat complex structures in the topset beds will result. During each period of shore retreat the previously formed topset beds near shore will be eroded, and during each advance fresh topset beds will be laid down unconformably on an eroded surface.

[1] W. M. Davis, *Geographical Essays* (Boston, 1909), pp. 702–3.

LITHOLOGICAL CHARACTER OF THE BEDS

The topset beds deposited during stillstand will constitute such a small proportion of the whole mass of sediment that geologically they will be of slight importance in uplifted shelf deposits. Oceanographic data indicate that the materials of which they are composed vary widely, ranging from gravel and sand to mud, with or without shells. The bulk of the deposit will consist of foreset beds built out over a thinner series of bottom-set beds in which extremely fine particles that have remained a long time in suspension will be present mixed with organic remains. Farther seaward these will grade into pure pelagic deposits.

TABLE I

A = Composite analysis of green and blue muds
B = Composite analysis of 78 shales

	A	B
SiO_2	57.05	58.38
TiO_2	1.27	0.65
Al_2O_3	17.22	15.47
Fe_2O_3	5.07	4.03
FeO	2.30	2.46
MnO	0.12	......
MgO	2.17	2.45
CaO	2.04	3.12
BaO	0.06	0.05
K_2O	2.25	3.25
Na_2O	1.05	1.31
P_2O_5	0.21	0.17
SO_3	......	0.65
S	0.13	......
CO_2	......	2.64
C	1.69	0.81 (organic)
H_2O	7.17	5.02
Other constituents	0.1964	......
	99.9964	100.46

Leaving aside volcanic and coral muds, which require special conditions for their formation, we find that, as shown by samples obtained from the continental slopes, blue muds and green sands and muds are the most common materials of the foreset beds, the former where the supply of waste is ample and the latter where the supply is more meager. Both of these are well represented

among the sedimentary rocks known to geologists, the former constituting shale and mudstone and graduating into marl, and the latter being represented by greensand and less pure glauconitic rocks. The samples obtained from the continental slope show well-marked stratification.[1] As Murray remarks: "The analogues of the now-forming terrigenous deposits are to be found in all geological periods."[2]

In this connection an instructive comparison can be made of the chemical analysis of a composite sample of 4 "green muds" and 48 "blue muds" from various parts of the continental slopes with that of a composite sample of 78 shales taken as giving the average composition of the argillaceous sedimentary rocks, but probably not by any means all of foreset origin. The analyses are given by Clarke.[3]

STRUCTURE OF A SHELF BUILT DURING POSITIVE MOVEMENT

Without going into the question of the possible causes of changes in the relative levels of sea and land the fact may be accepted that accumulation of sediment has in the past been very commonly accompanied by positive movement. No doubt positive movement is in some cases a rise in sea-level and in others a sinking of the floor upon which sediments are being laid down, and in still other cases a combination of both of these. It is convenient, however, in an investigation of the probable structure of shelf deposits, to regard all changes in the relation of the shelf to sea-level as vertical movement of the shelf rather than of sea-level. The latter will affect the relation of the sea to the neighboring land also, that is to say, it will be regional in its effects, and obviously precisely similar effects will be brought about by regional subsidence. By regarding the sea-level as fixed and the shelf as subsiding, however, we are able to investigate the effects of differential as well as regional changes of level.

To begin with, it may be supposed that a shelf of moderate dimensions has been built forward during a period of stillstand

[1] Sir John Murray, *The Ocean*, p. 213. [2] *Ibid.*, p. 234.

[3] F. W. Clarke, "The Data of Geochemistry," *U.S. Geol. Surv., Bull. 616*, 1916, p. 514 and p. 28.

throughout which there has been a steady stream of sediment from the land. If now this already formed shelf be supposed to subside very slowly, as the shelf sinks, the stream of waste supplied by rivers from the adjacent land may be reduced in volume, may remain sensibly constant, or may be increased in volume, according as the land subsides also, remains stationary, or is uplifted. Let us suppose, however, that the stream of waste is sufficiently continuous and the movement sufficiently slow to allow the shelf to be maintained during subsidence. Obviously maintenance on a sinking floor of a shelf with its outer edge at a fixed depth (approximately 100 fathoms) below sea-level involves deposition of material on the top of the shelf as well as, or instead of, in front of it. Less of the waste will be available for deposition as foreset beds than in the case of a shelf being built during a period of stillstand. The shelf will be built upward of material arrested in transit seaward owing to its being lowered below the depth at which wave action stirs it sufficiently to keep it in motion.

This accumulation of topset beds may attain an enormous thickness, as has been shown by Barrell to be the case in deltas, the thickness depending only upon the amount of subsidence during which a continuous supply of waste is kept up.

Assuming that during subsidence the supply of waste is always sufficiently abundant to insure the continuity of deposition of topset beds over at least a portion of the area, we may investigate the conditions of deposition of topset beds, foreset beds, and pelagic deposits, understanding by the latter term deposits formed either in moderatly deep or relatively shallow water where the supply of bottom waste fails, the deposit consisting of organic and minute inorganic particles settling from suspension ("flotation beds," Chamberlin).

The form of a single *stratum* deposited in a given time during stillstand will be that shown in Fig. 5*a*, that is to say, the bulk of the terrigenous sediment will be in the foreset portion, the edge of the shelf advancing seaward a considerable distance during the given time. With continuous subsidence in progress, however, the formation of thick topset beds may use up so much of the waste that there is little or none left to build the edge of the shelf forward.

If there is still a small advance there will be a terrigenous foreset bed, but it will be relatively thin (Fig. 5*b*). It is only a step from this case to one in which there will be no terrigenous foreset bed, the waste being just sufficient or even insufficient to build a topset bed for the full width of the built shelf, the edge of the shelf in the latter case retreating landward. In no case, however, will the continuity of a stratum be broken, for, if the foreset bed fails, the pelagic deposits will extend up the continental slope to join the topset bed (Fig. 5*c*).

During long-continued subsidence, the duration of which may be comparable with the length of a geological period, the movement

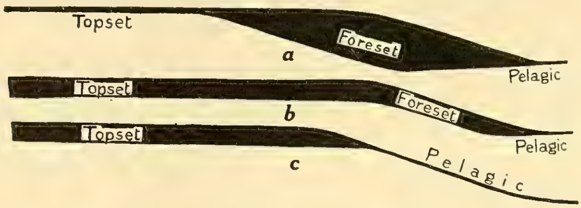

FIG. 5.—*a*, Variation in thickness of a stratum deposited during stillstand; *b*, a stratum deposited during subsidence with abundant supply of waste; *c*, a statum deposited during subsidence with restricted supply of waste.

is probably never absolutely uniform and continuous. The geological record affords evidence to the contrary, and what is known from physiographic evidence of the more recent movements points in the same direction. Oscillations being left out of account, consideration may be given to the consequences of fluctuations in the rate of subsidence. Clearly, with a constant rate of supply of waste, alternating periods of extremely slow and relatively rapid subsidence may determine alternating advances and retreats of the edge of the shelf. It is obvious also that, with slow subsidence at a uniform rate in progress, fluctuations in the supply of waste may produce similar results. Increase in the supply of waste may result from differential elevation of a portion of the neighboring land mass, after which a falling off will take place as a result of regional subsidence or peneplanation of the land, to be followed by a further increase when differential elevation is renewed, and so on.

The effects of fluctuations in the rate of subsidence of the sea floor and in the rate of supply of waste may be considered together. When the ratio of waste supply to rate of subsidence is sufficiently large the front of the shelf will advance (Fig. 6, *B*); and when this ratio is sufficiently low the front will retreat (Fig. 6, *C* or *D*).

Notable fluctuations in the value of the ratio will determine alternating periods of advance and retreat, and these alternations will produce interstratification of beds of very varied lithological character in the shelf deposits which are not without parallel in the known rocks.

In the landward portions of the shelf intercalations of subaërially deposited material may be present in the dominantly marine topset beds, as Barrell has shown to be the case in those portions of

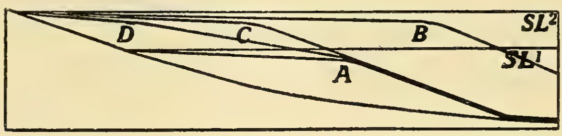

FIG. 6.—Diagram illustrating the growth of a shelf during a period of subsidence. *A*, edge of the shelf with sea-level SL^1; *B*, *C*, *D*, possible positions of the edge of the shelf with sea-level SL^2.

the shelf which are the submarine portions of deltas.[1] An instructive example of such alternation has recently been described by Stebinger.[2]

Farther seaward the mass of sediment deposited during subsidence may be for a considerable distance composed of marine topset material throughout. The texture of these topset beds will depend very largely upon the relief and also upon the nature of the rocks of the neighboring land; and it may be expected to vary vertically, fine sediments marking periods when the land has been reduced to low relief by erosion and coarser sediment marking periods of renewed differential elevation. The topset material will

[1] J. Barrell, "Relative Geological Importance of Continental, Literal and Marine Sedimentation," *Jour. Geol.*, XIV (1906), 353–54, Fig. 10, p. 445; "Criteria for the Recognition of Ancient Delta Deposits," *Bull. Geol. Soc. Am.*, XXIII (1912), 399, Fig. 4.

[2] E. Stebinger, "The Montana Group of Northwestern Montana," *U.S. Geol. Surv., Prof. Paper 90G*, 1914, pp. 61–68.

not, in general, be subjected to very prolonged chemical and mechanical disintegration on the shelf before being buried. When sandy it may contain, but little altered, grains of the less stable minerals of the shore rocks. If these rocks are predominantly igneous the topset sands when consolidated may form arkose or greywacke, similar to that forming the great bulk of the strata in the mountain ranges of New Zealand. Of these rocks, commonly ascribed to the Maitai System, Marshall writes:

> The material of which all these rocks is composed has been derived from plutonic masses, for they are composed of grains of quartz, feldspar, and hornblende or augite. . . . . The great thickness of the sediments shows that the area was one of deposition for a considerable time, though the general coarseness of the material shows that the deposition was relatively rapid, and took place on a coast-line. Presumably the coast-line fringed a large continental area, from the surface of which rivers carried large quantities of sand.[1]

Preservation of the grains of decomposable minerals, however, cannot safely be taken as certain proof of topset origin of the beds in which they occur, for it is conceivable that, with a very abundant supply of terrigenous material during a period of little or no subsidence, similar material might be buried in foreset beds.

Barrell[2] has indicated the origin of alternations of sandy and muddy layers of small thickness as a result of topset deposition. The sediment on the outer, deeper part of the continental shelf, near the maximum depth at which the bottom is ever stirred by wave action, is affected only by the waves produced by exceptionally severe storms, such as occur only once in a number of years. During the interval between two such storms an unsorted mixture of mud and fine sand accumulates. When a storm occurs, the gentle stirring of the bottom which it produces causes the finer particles of the superficial layer to go temporarily into suspension, the larger grains remaining as a layer of clean washed sand. After the storm, subsidence being continually in progress, another layer of sandy mud is laid down above the sand, and by the time the next great storm occurs the sand layer and the deeper part of the

[1] P. Marshall, *Geology of New Zealand* (Wellington: Government Printer, 1912), pp. 184–85.

[2] J. Barrell, "Criteria for the Recognition of Ancient Delta Deposits," *Bull. Geol. Soc. Am.*, XXIII (1912), 428.

overlying mud layer have been so deeply buried that they are secure from further disturbance. The sand of a superficial layer is, however, again washed clean, and so the process goes on until there are innumerable alternating sand and mud layers throughout a great thickness of strata.

Toward the outer part of the mass of sediment intercalations of foreset beds and pelagic deposits may be present in the topset beds owing to advances and retreats of the edge of the shelf corresponding to fluctuations in the ratio of waste supply to rate of subsidence, the possibility of which has been pointed out on an earlier page. In Fig. 7, which represents diagrammatically a section of a shelf

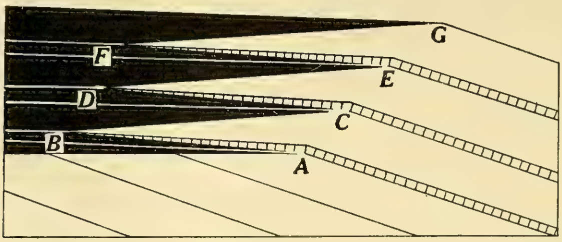

Fig. 7.—Alternation of lithological types in shelf deposits resulting from fluctuation in the ratio of supply of waste to rate of subsidence. Topset beds, black; foreset beds, white; pelagic beds, with cross-lines. The top of the shelf at successive stages is shown by the white lines. The vertical scale is exaggerated about ten times.

the front of which has alternately retreated and advanced during upward growth, *A* is the front of a shelf built forward during a period of stillstand preceding the subsidence, *B*, *D*, and *F* are positions of the front after episodes of small ratio of waste supply to rate of subsidence, and *C*, *E*, and *G* are positions of the front after episodes during which this ratio has had a large value. In order to simplify the diagram the lateral transitions from one type of sediment and from one slope to another are represented as perfectly sharp, but it must be borne in mind that in nature these transitions are gradual.

An inspection of this diagram makes it clear that above *A* there will be in the region represented by the middle part of the diagram the following succession:

10	Topset beds........	Coarse- to fine-grained sandstone, arkose, and greywacke, with interbedded shale or argillite.
9	Foreset beds.......	More or less calcareous bluish mudstone or greensand.
8	Pelagic beds........	Argillaceous to pure limestone, perhaps glauconitic, or somewhat sandy.
7	Topset beds........	As above.
6	Foreset beds.......	As above.
5	Pelagic beds........	As above.
4	Topset beds.	
3	Foreset beds.	
2	Pelagic beds.	
1	Topset beds.	

Farther seaward there will be no intercalations of topset deposits, but an alternation of limestone bands with bluish mudstone,

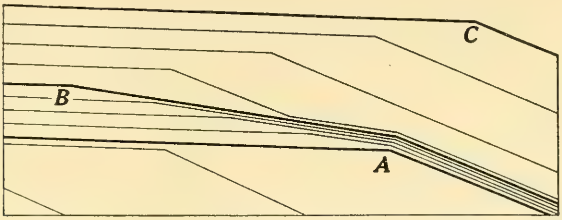

FIG. 8.—Enlargement of the portion *ABC* of Fig. 7

marl, or greensand. In this way may perhaps be explained the intercalation of the Amuri limestone of New Zealand, between mudstone and marl in Marlborough, and between greensand and glauconitic sandy limestone passing upward into marl in North Canterbury, and also the intercalation of the Oamaru limestone between beds of greensand in Otago, New Zealand.

The intercalations of foreset beds in the pelagic deposits will become more calcareous and thinner and will finally die out seaward. Obviously, under certain conditions of restricted waste supply this may occur in moderately shallow water, the proportion of foreset beds in the whole mass of sediment being very small.

In Fig. 7, which is designed to represent the vertical distribution of lithological types, the continuity of strata is not apparent, but in Fig. 8, which is an enlargement of the portion *ABC* of Fig. 7, the

continuity of strata is shown. It will be seen that in the section *AB*, built during the period of retreat of the shelf front from *A* to *B*, the topset beds will pass laterally into pelagic deposits, and that in the section *BC*, built during the period of advance from *B* to *C*, the first-formed strata will pass somewhat rapidly through foreset beds into pelagic deposits. In the later-formed strata of the section *BC*, however, the foreset portions will assume greater importance, the transition to pelagic deposits taking place in the deeper water farther seaward.

STRUCTURE OF A SHELF BUILT DURING NEGATIVE MOVEMENT

Negative movement generally involves uplift of the adjacent lands as well as of the sea floor. So erosion will as a rule be revived and the supply of waste increased. Also as the sea retreats the former surface of the shelf will be subject to subaërial and marine erosion, producing a further supply of waste. Negative movement will therefore be generally accompanied by heavy sedimentation on the continental slope.

It is conceivable, therefore, that the shelf may grow seaward with sufficient rapidity to maintain its edge at the usual depth throughout a period of rather rapid movement. During such movement the width of the shelf (measured from the ever-changing shore line) may diminish, remain constant, or even increase. In the first case the topset slope will be steepened by submarine erosion, and in the last case it will become less steep owing to deposition of topset beds. With constant width will go constant slope, with neither deposition nor erosion, the erosion that goes on at the shore line affecting only the emerging land.

From the foregoing it appears that, while topset beds are not necessarily absent, they can be only very thin, and they will be largely removed by erosion as the shelf emerges. The bulk of the deposit forms foreset beds, and the material of these will be of somewhat coarse texture.

THE NORTHWARD EXTENSION OF THE PHYSIOGRAPHIC DIVISIONS OF THE UNITED STATES

W. N. THAYER
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PART I

INTRODUCTION

Preliminary to a study of the economic bearing of the physiography of North America the writer found it desirable to inquire into the extension of the generally recognized physiographic divisions of the United States southward into Mexico and northward into Canada and Alaska. The results of the study of Mexican physiography were published in the *Journal of Geology* early in 1916.[1] The present paper embodies the results of an investigation of the northward extent of these divisions.

The plan of this paper is to discuss briefly the physiographic divisions of the United States which touch our northern border, and to compare with them the adjacent territory north of the International Boundary by reference to surface features, boundaries, structure, and physiographic history, and by this means to show that the divisions of the United States have northern extensions that project them far into Canada and in some places into Alaska.

This paper is avowedly one of correlation, and no effort has been made to give detailed descriptions of the Canadian or Alaskan areas. Such work must be left to the future, as there are still large expanses of territory that have never been fully explored, much less studied, with care sufficient to allow an accurate classification of surface features or the drawing of permanent boundaries. The generalizations advanced in this paper will, of course, be subject to change as our knowledge of the north country increases.

Fenneman's classification has been used wherever it could be adapted to the continental scope of this paper. The writer's own

[1] W. N. Thayer, *Jour. Geol.*, XXIV (1916), 61–94.

experience and field study have contributed in a small way to the text, but he has also drawn liberally on the published work of others. He is particularly indebted to Dr. N. M. Fenneman for advice and criticism.

THE COAST RANGES SECTION OF THE PACIFIC BORDER PROVINCE

The term "Coast Ranges" may be used with perfect freedom when discussing topographic features within the United States, because in both popular and scientific thought the mountains designated by the term are quite definitely delimited. Freedom in the use of the term is restricted beyond the International Boundary, however, for in Canada there is also a "Coast Range" in no way related to the "Coast Ranges" of the United States, and the name is very definitely fixed in the language of the people as well as in scientific usage. It becomes necessary, therefore, to distinguish these features by appropriate terms that shall leave no room for ambiguity. This will be done in the present paper by the expedient of using the plural form, "Coast Ranges," for those mountains both in the United States and in Canada which face the open ocean and the singular form, "Coast Range," for that Canadian member of the Pacific System which is separated from the open ocean by numerous mountainous coastal islands. The two features have but little in common and differ widely in their records of physiographic history.

The mountains that border the coast of the United States from the Sierra de Los Angeles to the straits of San Juan de Fuca "are neither a single range nor alike in character and history, but they are for the most part contiguous and may be treated as a single general province."[1] A similar characterization may be made of the mountains of Vancouver and Queen Charlotte islands, the Alexander Archipelago, the St. Elias group, the Kenai Peninsula, and Kodiak Island, and for the same reasons they may be considered as an extension of the Coast Ranges of the United States and as belonging to the same province.

There is some objection to this broad view, particularly because a large part of the region north of the forty-ninth parallel has not

[1] N. M. Fenneman, *Ann. Assoc. Am. Geog.*, IV, 133.

been studied in detail, but it is supported in a general way by numerous geologists who have studied portions of the northwest coast of North America. Dawson,[1] Ransome,[2] and Clapp[3] tentatively place the mountains of Vancouver and Queen Charlotte islands in the province with the Coast Ranges, and Willis and Smith[4] are definitely committed to the idea. Bancroft[5] says that the system of the Coast Ranges is continued northward along the coast of Alaska in the mountainous islands of the Alexander Archipelago, and that these islands express the probable continuity of a range that formerly bridged all gaps existing between the Olympic Mountains of Washington and the St. Elias group of Alaska. Brooks[6] continues the system northward, connecting the Alexander Archipelago with the St. Elias group and that group, through the Chugach Mountains, with the mountains of the Kenai Peninsula and Kodiak Island.

The four more or less dissimilar divisions of the Coast Ranges in the United States have this in common—they represent dissected peneplains. Topographically they consist of individual ridges, and, excepting the Klamath Mountains, they follow the contour of the coast with considerable parallelism between them. The tops of the ridges are generally flat and the upland has a rolling, mature character, with peaks rising here and there above the general level. These peaks are residuals or monadnocks that resisted erosion during the first cycle. Diastrophism and vulcanism have contributed something to the present topography, but, though locally prominent factors, they have been generally subordinate to erosion.

The drainage of the Coast Ranges is a reliable index to the causes that have produced the present topography. The larger westward-flowing streams, that is, those which cut across the ranges to empty their waters directly into the Pacific, are without exception antecedent. They have preserved the courses which they

[1] G. M. Dawson, *Bull. Geol. Soc. Am.*, XII, 61.

[2] F. L. Ransome in *Problems of American Geology* (Yale University Press), p. 359.

[3] C. H. Clapp, *Geol. Survey Canada, Guide Book No. 8*, Part III, p. 280.

[4] Bailey Willis and G. O. Smith, *U.S. Geol. Survey*, Folio 54.

[5] J. A. Bancroft, *Geol. Survey Canada, Mem. 23*, p. 18.

[6] A. H. Brooks, *U.S. Geol. Survey, Prof. Paper 45*, pp. 27–42.

formerly had while the old surface was being subdued. The Sacramento and Columbia rivers are prominent examples of this type.

TABLE TO EXPLAIN THE ACCOMPANYING MAP

Major divisions, the strongly characterized parts of the continent, are separated by *heavy* lines, and are distinguished by Arabic numerals; *Provinces* are separated by *light* lines, and are distinguished by letters; *sections* are distinguished by Roman numerals.

Major Divisions	Province	Section
1. Laurentian Plateau	(*a*) Laurentian Plateau proper (*b*) Superior Highlands (*c*) Adirondack Mountains (*d*) Unnamed	
2. Atlantic Plain	(*a*) Continental shelf (*b*) Coastal Plain...........	I. Atlantic section II. Gulf section III. Yucatan section
3. Appalachian Highlands	(*a*) Piedmont region (*b*) Blue Ridge Mountains (*c*) Appalachian Valley (*d*) St. Lawrence Valley (*e*) Appalachian Plateaus (*f*) New England region	
4. Interior Plains	(*a*) Interior Low Plateaus (*b*) Central Lowland........ (*c*) Great Plains (*d*) Wyoming Basin (*e*) Texas Hill region (*f*) Canadian Great Plains (*g*) Anatuvuk Plateau	I. East. Lake section II. West. Lake section III. Driftless area IV. Till plains
5. Interior Highlands	(*a*) Ozark Plateau (*b*) Ouachita region.........	I. Arkansas Valley II. Ouachita Mountains
6. Rocky Mountain System	(*a*) Southern Rockies (*b*) Boundary group (*c*) Mackenzie Mountains (*d*) Endicott Mountains	
7. Intermontane Plateaus	(*a*) Columbia Plateau (*b*) Colorado Plateau (*c*) Basin-and-Range province (*d*) Interior Plateaus (*e*) Yukon Plateau (*f*) Sonoran Desert (*g*) Anahuac Desert Plateau (*h*) Sierra Madre	
8. Pacific Mountain System	(*a*) Pacific Mountains.......	I. Sierra Nevada II. Cascade Mountains III. Coast Range of British Columbia IV. Coast Range of Alaska
	(*b*) Pacific Border province...	I. California trough II. Puget trough III. Copper River basin
	(*c*) Coast Ranges...........	I. California-Oregon-WashingtonRanges III. Alaskan Ranges
9. Southern Mexican Highlands	(*a*) Volcanic province (*b*) Sierra del Sur province	
10. Isthmian Lowlands	(*a*) Tehuantepecan province	

The streams now occupying the longitudinal valleys have in part inherited courses from the earlier cycle, but they generally follow structural lines or have had their courses determined by folding

since the period of peneplanation (as in the Olympic Mountains), and are therefore subsequent.

In certain places, particularly in northern California, this section includes, besides the mountains proper, a tract of dissected

plateau immediately adjacent to the coast. This tract was eroded to the condition of a peneplain and later uplifted and dissected into its present form.[1] Local subsidences following the uplift drowned the lower courses of certain master-valleys, notably those of the Sacramento and Columbia rivers.

Although a large part of the Canadian division of the Coast Ranges has not been studied or mapped, a survey of the literature and maps available shows how similar are its topographic features to those in the United States. The topography of this division also represents a dissected peneplain, with residuals rising above the general level.[2] This region was extensively glaciated during the Pleistocene epoch, and many topographic features were developed which are not found farther south, such as smoothed and rounded mountains, scoured and terraced valleys, fiords, and superposed streams. However, when large areas are considered the topographic features appear to be analogous to those of the United States. A noteworthy similar feature is the coastal peneplain developed along the western margin of Vancouver Island. Associated with this are also wave-cut terraces, such as characterize the coastal peneplain in the United States, and in places a very irregular coast line due to later depression.

It is difficult to compare the topography of the Alaskan division of the Coast Ranges with that of the United States on account of the pronounced effect of Pleistocene and Recent glaciation, particularly in the mountains of the Alexander Archipelago and the St. Elias Range. However, two conditions necessary to link this division to the remainder of the Coast Ranges have been definitely established. The mountains of Kodiak Island and the Kenai Peninsula present an upland surface which can scarcely be interpreted as other than the remnants of an ancient peneplain,[3] and there is abundant evidence of instability dating from early Tertiary to the present time. Another correlating feature may be found in the course of Alsek River across the St. Elias Range. This is probably an antecedent stream course, analogous to those of the Columbia and Sacramento rivers. The course of Copper River

[1] A. C. Lawson, *Univ. Cal. Bull.*, I, 242–44.

[2] C. H. Clapp, *op. cit.*, pp. 282–84.

[3] A. H. Brooks, *op. cit.*, p. 272.

across the Chugach Mountains may also fall within this classification.

The physiographic history of the Coast Ranges in the United States begins with the general uplift in the Pliocene period that started the erosion cycle which produced the first peneplain. During this cycle the master-streams outlined their present courses. The date of the uplift that began the present erosion cycle has not been definitely determined, but it may be assigned tentatively to late Pliocene time. The present topography, excepting residual peaks, and all tributary stream courses are the results of dissection during this later cycle.

North of the International Boundary there are records of a corresponding sequence of events. Diastrophism on a large scale was the dominant process during the Tertiary period until the close of the Miocene epoch. Erosion following an uplift, probably in Pliocene time, subdued the mountains of Vancouver and Queen Charlotte islands[1] and also the mountains of Kodiak Island and the Kenai Peninsula,[2] and it may fairly be assumed that it included the intermediate members of the Coast Ranges.

THE PACIFIC TROUGH SECTION OF THE PACIFIC BORDER PROVINCE

The great depression of the western coast of North America, known as the Pacific Trough, is a structural feature that extends, with minor interruptions, from Cape Corrientes, Mexico, northward to Alaska. It is made up of six natural divisions: the first and southernmost is the Gulf of California; the lowlands of the Lower Colorado Basin constitute the second; and the third is the Great Valley of California. The fourth comprises the Willamette and Cowlitz valleys and Puget Sound. The fifth or Canadian division extends northward from the Straits of San Juan de Fuca and includes the Straits of Georgia, Queen Charlotte Sound, and probably Hecate Straits. The sixth or Alaskan division extends apparently through Clarence and Chatham straits to Lynn Canal. The mountains of the St. Elias group interrupt the extension of the trough northward from Lynn Canal in very much the same manner as do the Klamath Mountains of the United States, but it is

[1] G. M. Dawson, *op. cit.*, p. 90. [2] A. H. Brooks, *op. cit.*, pp. 292, 293.

probably continued beyond them through the Copper River Basin, Sushitna Basin and Cook Inlet, and possibly includes the Shelikof Straits.

The divisions represented by the Lower Colorado Basin, the Great Valley of California, the Willamette and Cowlitz valleys, the Copper River Basin, and the Sushitna Basin are land surfaces; the remaining divisions are at present submerged. Within the United States the eastern and western boundaries of the subaërial divisions may be definitely drawn. The floor of the Great Valley is, for example, practically coextensive with the area of Quaternary deposits shown on geologic maps, and in Oregon and Washington the greater part of the depression is filled with glacial or fluvio-glacial deposits and alluvium formed during or since the glacial period. Brooks[1] uses the same criterion to delimit the terrane of the Copper River Basin, which he describes as a broad floor of Pleistocene gravel and silt deposits extending from the inland slope of the Chugach Mountains to the foothills of the Alaska Range. The boundaries of the submerged divisions may be regarded as practically coincident with the limiting shore lines.

The topography of the subaërial divisions within the United States may be characterized as a "floor." The broad, sloping alluvial plains of these sections are generally featureless. The slope of the valley floor generally increases toward the foothills, finally merging with the alluvial fans in the foothill gulches. In some places this merging is so gradual that it is impossible to say where plain ends and foothills begin. Brooks has applied the term "floor" to the Alaskan section and emphasizes its monotonous lack of relief.

"The Pacific Coast downfold has been a feature of the western coast since the Cretaceous period, and during several geologic periods was so deeply depressed as to lie beneath sea-level and receive a considerable body of sediments."[2] These marine sediments, however important geologically, do not contribute in any way to the present topography. The physiographer is concerned chiefly with the origin of the later alluvium and gravel deposits, which were produced by stream action after certain parts of the trough had been cut off from the sea. These deposits were of

[1] A. H. Brooks, *op. cit.*, p. 54. [2] Isaiah Bowman, *Forest Physiography*, p. 177.

course derived from the adjacent highlands, both to the east and west, and therefore the history of the growth and dissection of the mountains is in a large measure the history of the filling of the trough.

The mountainous province which borders the trough on the east has been contributing deposits since Cretaceous time. The Coast Ranges were probably sufficiently elevated in early Pliocene time to commence contributing to the filling of the trough. In late Pliocene time both mountain systems were further uplifted, increasing the carrying power of the streams and resulting in a more rapid filling of the depression. By the close of the Pleistocene epoch the deposits had accumulated to such a depth in certain places as to fill the trough to sea-level and to cut off parts of it from the sea. From that time to the present the history of the subaërial divisions has been that of flood-plain formation.[1] These facts apply chiefly to the divisions within the United States, but the deposits of the Copper River basin also bear evidence of a similar sequence of events in that division.[2]

The history of the submerged parts of the trough is important only as it contributes to the discussion of the land surface. The history of the Gulf of California has been recounted in the writer's paper on Mexico previously cited,[3] and Willis and Smith[4] have given a good summary of the history of Puget Sound. A review of the literature on the subject would lead one to believe that an identical series of events took place within the submerged parts of the trough in Canada and Alaska. From the data available at this time, however, it is impossible to make a positive statement.

THE SIERRA-CASCADE PROVINCE OF THE PACIFIC MOUNTAIN SYSTEM

This province comprises a very persistent mountainous feature of Western North America in which folding came to a close in Mesozoic time and which has since been comparatively rigid.[5] The

[1] F. L. Ransome, *Univ. Cal. Bull.* (Dept. Geol.), I, 387.

[2] A. H. Brooks, *op. cit.*, p. 54; also W. C. Mendenhal, *U.S. Geol. Survey, Prof. Paper 41*, p. 84.

[3] W. N. Thayer, *op. cit.*

[4] Bailey Willis and G. O. Smith, *op. cit.*

[5] F. L. Ransome in *Problems of American Geology*, pp. 358, 359.

various members of the mountain system are bound together in one great structure by a chain of batholiths, the intrusion of which seems to have begun in the north and continued progressively southward during a long period of time.[1]

The members of this mountain system in the United States are the Sierra Nevada, the Klamath Mountains, and the Cascade Mountains. To these might be added the Blue Mountains of Oregon. The Northern Cascade Mountains are generally regarded as ending at the International Boundary, but as a matter of fact they terminate naturally a few miles beyond the boundary at the canyon of Fraser River. Daly[2] has selected this as a dividing line, according to his plan of limiting physiographic units by master-valleys and trenches.

This province includes a section in Canada known as the Coast Range of British Columbia—a mountainous belt about 100 miles wide which extends along the coast for nearly 900 miles from the canyon of Fraser River northwestward beyond the head of Lynn Canal. Dawson[3] early objected to admitting the Coast Range to the same classification as the Cascades because of the decided difference in rock composition. Physiography, however, gives preference to structure and topography as criteria for classification, and, as Daly[4] has pointed out, "it has become more and more evident as the study of the Cordillera progresses that rock composition can never rival crest continuity as a primary principle in grouping the western mountains."

At its northern end the Coast Range passes behind the St. Elias Range and gradually blends with the Interior Plateaus near Lake Kluane.[5] Although this particular member terminates here, the province, following the trend of the other Cordilleran divisions, continues along a great arc to the northwest and embraces an Alaskan section of several members—in succession the Chigmit Mountains, the Alaskan Range, and the Aleutian Range.[6] In all

[1] A. C. Lawson, *Jour. Geol.*, I, 579–86.

[2] R. A. Daly, *Geol. Survey Canada, Mem. 38*, Part I, p. 41.

[3] G. M. Dawson, *Trans. Royal Soc. Can.*, sec. 4, p. 4.

[4] R. A. Daly, *op. cit.*, p. 40.

[5] J. A. Bancroft, *Geol. Survey Canada, Mem. 23*, p. 13.

[6] A. H. Brooks, *op. cit.*, pl. 7.

probability the system also includes the volcanic Aleutian Islands. In the absence of adequate data on the mountains of Alaska it should be remembered that any classification is merely tentative and is subject to revision as knowledge of the country becomes more thorough. However, there is considerable evidence to support the present classification. This will be given in the discussion of the topography and physiographic history of the region.

In a general way the topography of this province, particularly Sierra Nevada and Cascade mountains, is that of an uplifted (Tertiary) peneplain, which has been deformed by folding and faulting, deeply dissected by erosion, and covered deeply in places with volcanic products.[1]

The Sierra Nevada is a bold, continuous, and deeply dissected range, about 75 miles wide, with a crest line of well-defined residual peaks. The mountains are delimited on the east for hundreds of miles by a high and steep fault-scarp, but descend gradually to the Great Valley on the west across a gently sloping plateau.

The Cascade Mountains have also, in most places, a broad, maturely dissected summit of about the same width as that of the Sierras, above which rises a straight north-south line of several scores of volcanic peaks. Long, broad, flat-topped spurs, analogous in some respects to the crest of the High Sierras, diverge from these peaks. The eastern slope of the Southern Cascades is bold and the western slope gentle. In these respects also they resemble the Sierras. In the Northern Cascades, however, the eastern slope loses its abruptness and the peneplain of the mountains descends gradually to the plateau of the Columbia River.

Three types of volcanic products have contributed to the making of the present topography of the Sierra Nevada and Cascade mountains: (1) batholithic granite and diorite intrusives, (2) flows of basaltic lava, and (3) andesitic cones which rise above the general level and dominate the view from many points.

The drainage of these sections of the province is characteristic of its type of topography. The courses of the forks of Feather River across the crest of the Sierra Nevada, the course of the

[1] J. S. Diller, *U.S. Geol. Survey, Bull. 353*, p. 9; also I. C. Russell, *U.S. Geol. Survey, 20th Ann. Rept.*, Part II, p. 140.

Columbia River across the Cascade Mountains, and that of the Skagit River across the Skagit Mountains were outlined upon the surface of a Tertiary peneplain and have been maintained in spite of uplift to the present time. Most of the smaller streams are subsequent and have had their courses determined by structure or the relative hardness of rocks. Many of these latter have also had their courses altered by lava flows.

The Coast Range of British Columbia has a structure analogous to that of the Sierra Nevada and Cascade mountains,[1] and its topography is strikingly similar. These mountains are also the remnants of an uplifted and dissected (Tertiary) peneplain, the relief of which has been increased by later "warping, flexure, or displacement."[2] They are from 60 to 100 miles in width and of fairly uniform height. Many residual peaks rise along the crest line to a considerable elevation above the general level. Where erosion has removed the overlying sedimentary rocks a number of great batholiths are exposed, which may be regarded as connecting the Coast Range structurally with the southern members of the system. The eastern slope of the mountains is very gentle, as in the Northern Cascades, and in many places it merges insensibly with the Interior Plateaus.[3]

The principal rivers which flow across the Coast Range from the interior are antecedent to the uplift, and have maintained to the present time courses which they originally established on peneplaned surface that sloped westward to the ocean. Chief among these are the Fraser, Stikine, and Taku.[4]

It is difficult to give a clear summary statement of the topography of the Alaskan section on account of the small amount of geological work and mapping that has been done. Suffice it to say, however, that the Chigmit and Alaska ranges are bold, mountainous features, and the available evidence indicates that they have been carved from a Tertiary peneplain after differential uplift.

[1] A. C. Spencer, *U.S. Geol. Survey, Bull. 287*, pp. 10, 11; also G. O. Smith, *U.S. Geol. Survey*, Folio 86.

[2] A. C. Spencer, *Bull. Geol. Soc. Am.*, XIV, 117–32.

[3] R. G. McConnell, *Geol. Survey Canada, Guide Book No. 10*, pp. 7–11.

[4] A. H. Brooks, *op. cit.*, p. 271.

This fact has not been fully established, however, and since there is apparently no accordance of summit levels, the origin of these mountains may still be open to question. The Aleutian Range with its long line of typical cones built along an anticlinal axis closely resembles the Cascades. As a matter of correlation it may be remarked that intermittent vulcanism has continued in both sections to the present time.[1]

The physiographic history of this province properly begins with the emergence of the area from the sea at or near the close of the Mesozoic era. Deformation either accompanied the emergence or closely followed it, and then from a point as far north as the sixtieth parallel to the southern end of the Sierra Nevada folding on a large scale came to a close. Since Cretaceous time the system has been comparatively rigid, and its various units in so far as they have moved at all have moved *en masse* or in large fault-blocks.[2]

The present mountains, however, were not produced by deformation only. Several forces have worked together from the close of the Mesozoic era to the present time to produce the topography as we now see it. This will be shown in a brief summary sketch of the history of the various units.

In the Sierra Nevada the present simple orographic form is strikingly contrasted with an older and quite complex structure which was developed during the Mesozoic deformation, and which consisted of strong folds intruded by extensive granodiorite batholiths. In late Cretaceous time these folds were truncated by erosion and the surface reduced to one of low relief.[3] The Eocene epoch was probably a time of mild deformation and uplift. This began an erosion cycle that culminated in the Miocene epoch by reducing the area to a peneplain.[4] Another uplift late in the Pliocene epoch raised this peneplain to the level of the plateau, now dissected, which lies between the crest of the Sierras and the Great Valley. The crest of the Sierras, or, as it is frequently called, the High Sierras, stands several thousand feet above the general level

[1] A. H. Brooks, *op. cit.*, p. 275.

[2] F. L. Ransome, in *Problems of American Geology*, pp. 358, 359.

[3] F. L. Ransome, *op. cit.*, p. 351.

[4] J. S. Diller, *U.S. Geol. Survey, 14th Ann. Rept.*, Part II, pp. 404–11.

and is not a part of the Miocene peneplain. It is the residual part of the surface that was reduced in late Mesozoic time.[1]

A similar record of events is preserved in the Cascade Mountains. A range corresponding to the present Cascades was probably formed by folding during the Mesozoic era accompanied by intrusions of igneous rock, but the configuration of the present range is ascribed to later events and processes. In early Tertiary time the region was comparatively rugged. During the earlier epochs of the Tertiary period there was an alternation of basaltic lava flows and shallow water deposition. The Miocene epoch was a time of further mild deformation, followed by an erosion interval that subdued the whole region. This subdued surface was uplifted during the Pliocene epoch to form the mass of the present Cascade Range.[2] Erosion and vulcanism have since combined to produce the present topography from this uplifted peneplain.

On a previous page an attempt was made to justify the classification of the Coast Range of British Columbia with the Sierras and Cascades on a basis of crest-continuity. A further justification is found in the record of the physiographic history of the Coast Range. The later part of the Mesozoic era was in this region also a time of deformation and granitoid batholithic intrusion. Erosion followed this deformation and produced a peneplain, or at least a subdued surface. Milder deformation, probably in the Miocene epoch,[3] uplifted this subdued surface, and another erosion cycle was started, which before the close of the Pliocene epoch had produced a second peneplain. Late Pliocene time witnessed another uplift and the beginning of the erosion cycle that produced the topography as it now appears.

Writers do not all agree regarding the Tertiary peneplains of the Cascades and the Coast Range of British Columbia, the existence of which is inferred from the accordance of summit levels. Russell[4] and Willis and Smith[5] agree on a late Tertiary base level

[1] Isaiah Bowman, *op. cit.*, p. 170.

[2] G. O. Smith, *U.S. Geol. Survey*, Folio 86.

[3] A. C. Spencer, *Bull. Geol. Soc. Am.*, XIV, 117–32.

[4] I. C. Russell, *U.S. Geol. Survey, 20th Ann. Rept.*, Part II, pp. 140–44.

[5] Bailey Willis and G. O. Smith, *U.S. Geol. Survey, Prof. Paper 19.*

produced according to the peneplain theory of Davis. Daly[1] opposes this idea, however, in so far as it applies to the region under discussion, and explains the accordance of summit levels on a different principle. Without attempting to pass upon the relative merits of the theories, it may be remarked that the general topographic features are at least consistent with the peneplain hypothesis.

The sequence of physiographic events in the Alaskan section is difficult to determine. A probable summary is as follows: first, crustal disturbance in the late Mesozoic era and the opening of numerous volcanic vents at about the same time; second, peneplanation toward the close of the Tertiary period; and third, later differential uplift and erosion that in a large measure contributed to the present topography.[2] Though this statement should be accepted as subject to revision as our knowledge of Alaskan geography and geology increases, it appears probable that the major events of physiographic history in Alaska have followed the schedule described for the remainder of the province.

THE INTERMONTANE PLATEAUS

East of the mountains of the Pacific System lies a broad belt of country which, though characterized in many places by mountains and valleys or basins, presents on the whole a plateau surface, in part degraded, in part constructional. This belt of plateaus extends from Mexico northward to the Bering Sea and includes the Great Basin, Colorado and Columbia plateaus of the United States, the Interior Plateaus of British Columbia, and the Yukon Plateau of Alaska. It is bounded throughout its entire extent on the east by the Rocky Mountains.

Although there is some diversity of surface features among the several units of this intermontane belt, particularly between widely separated units, there is sufficient similarity among them in the relation of each to the adjoining provinces on the east and west, in their principal structural features, and in their records of

[1] R. A. Daly, *Geol. Survey Canada, Mem. 38*, pp. 631–41.

[2] A. H. Brooks, *op. cit.*, pp. 290–95.

physiographic history, to enable us to classify them as closely related provinces of a single major division.

Topographically the Great Basin is a region of fault-block mountains and detritus-filled valleys or basins, with small areas of horizontal lava flows scattered over its surface. Its altitude is everywhere lower than that of the bordering provinces. Ransome says that "the impressive feature of the Great Basin . . . . to one . . . . who looks over it from the crest of the Sierras or from the edge of the Colorado plateaus in Arizona is that it is a collapsed region."[1] The western boundary is characterized throughout almost its entire length by a fault-scarp that rises sharply to the crest of the Sierras. The eastern boundary is in some places a prominent scarp and in others a gentle slope from the adjacent highlands.

The Columbia Plateau, although built of almost horizontal lava flows and lacking on the whole the detrital filling of the Great Basin, is not to be sharply separated from it. Fenneman[2] shows a broad transition zone between the two divisions. This province, like the Great Basin, also lies between and beneath two mountain provinces.

Prior to the extrusion of the lavas which now form its surface the Columbia Plateau was a region of rugged topography,[3] probably not unlike the Great Basin before the beginning of the period of basin-filling. This rugged surface was not entirely obscured by the lavas, as witness the Blue Mountains of Oregon. There is some evidence that there may have been a fault-scarp separating the plateau from the Cascades, but if such was the case it has been obscured by the lavas, and today the eastern margin of the peneplain of the Cascades descends gradually to the plateau of the Columbia apparently without a break.

The similarity between the Columbia Plateau and the Interior Plateaus of British Columbia is striking, although the two provinces are not contiguous, being separated a distance of something less than 100 miles by the Colville Mountains, which stand like a bridge across the plateaus and connect the Rockies with the Cascades.

[1] F. L. Ransome, *op. cit.*, p. 343. [2] N. M. Fenneman, *op. cit.*, pl. 2.

[3] I. C. Russell, *U.S. Geol. Survey, Bull. 199*, p. 61.

A large area of the Interior Plateaus is covered by basaltic lava flows of the same age as those of the Columbia Plateau, and where these are favorably disposed for observation it may be seen that they obscure a former rugged relief.[1] The present topography is conditioned, however, by factors other than lava flows and anterior relief. It represents in part dissected lava tables, in part dissected local peneplains of pre-Miocene age, and in part dissected mountain torsos reduced during early Tertiary and Mesozoic times.[2] In general, the topography may be described as a series of gently undulating and plateau-like uplands, from 4,000 to 6,000 feet in altitude, within which the streams have cut wide and deep valleys.

A significant feature of the Interior Plateaus, in fact, of the entire belt of Intermontane Plateaus, except the Great Basin, is the antecedent drainage. The basalt cover of the plateaus, originally horizontal, was later deformed, but the deformation was not rapid enough to affect seriously the streams that had been laid out on nearly flat lava sheets in response to initial slopes, and which have maintained their courses to the present day. Where there have been great uplifts we now find deep canyons. The Columbia River where it crosses the province is typical of this condition, as are also the Fraser, Skeena, Nano, Stikine, and Taku rivers.[3]

The Interior Plateaus lie below two adjacent and limiting provinces and are similar in this respect to the Columbia Plateau and the Great Basin. The eastern boundary is not marked by a prominent topographic break at any place, but a difference of surface features may be easily distinguished within a few miles. On the west, where the Interior Plateaus are bordered by the Coast Range, the boundary of the province is difficult to determine. The mountains and plateaus merge insensibly in many places[4] and present a case analogous to that of the Cascades and the Columbia Plateau in Washington.

The Interior Plateaus of British Columbia are continued northward into Yukon Territory and Alaska under the name of Yukon

[1] L. Reineke, *Geol. Survey Canada, Mus. Bull. 11*, Fig. 1 and p. 38.

[2] R. A. Daly, *Geol. Survey Canada, Guide Book No. 8*, Part II, p. 164.

[3] A. C. Spencer, *Bull. Geol. Soc. Am.*, XIV, 125–28.

[4] R. G. McConnell, *Geol. Survey Canada, Guide Book No. 10*, p. 11.

Plateau. There is no natural dividing line between these two units, and any line that is drawn to separate them must be arbitrary. No dividing line is necessary except for convenience in discussion, and for this purpose the political boundary between British Columbia and Yukon Territory is as satisfactory as any other, particularly as it practically coincides with the watershed that separates the headwaters of the Yukon River from the rivers flowing southward.

Topographically this division is a dissected plateau. The summits are accordant on the whole, though here and there isolated residuary masses rise above the general level.[1] Structurally the area has the form of a "broad shallow trough pitching to the north, whose axis coinciding with the valley of the Yukon trends northwest to the Arctic circle and then bends to the southwest. In other words, the trough makes nearly a right-angled bend and pitches toward Bering Sea."[2]

The Yukon Plateau has an altitude of 4,000 to 5,000 feet where it is bordered by the Coast Range, falling near the center to about 3,000 feet, and rising again as it approaches the Rockies. Along a part of the southwest margin the plateau abuts almost directly against the slopes of high mountain ranges, and so abrupt is this change from the smooth, flat summits of the upland to the rugged mountains that it is very suggestive of a fault-scarp.

It is apparent that the Yukon Plateau may be correlated with the other members of the Intermontane Plateaus, not only because of general similarity of surface features, but also because it lies between two mountain provinces. The probable fault-scarp along the western border suggests an analogy to that between the Great Basin and the Sierra Nevada. In fact, Brooks states specifically that the "Yukon Plateau is coextensive (continuous) with the plateau of British Columbia and can be regarded as belonging to the same physiographic province as the Great Basin."[3]

Along the remainder of the western border, however, the relation between plateau and mountains is more like that existing between the Coast Range and the Interior Plateaus or between the Cascades and the Columbia Plateau. This is particularly true

[1] F. E. Wright, *Geol. Survey Canada, Guide Book No. 10*, pp. 53, 54.

[2] A. H. Brooks, *op. cit.*, p. 278.

[3] A. H. Brooks, *op. cit.*, p. 41.

in the region adjacent to White and Chilkoot passes, and in the vicinity of White and Stikine rivers. In these places the summit plateau of the mountains blends with the plateau of the interior.[1]

The physiographic history of the Intermontane Plateaus is coincident with that of the mountain provinces bordering them on the west down to Eocene time,[2] and since the latter has been discussed in preceding pages it will not be necessary to repeat it here. The Eocene epoch witnessed widespread volcanic action of great magnitude in the Columbia Plateau division, and lesser, localized action in the northern divisions, accompanied by an uplift of the previously subdued surface. An erosion interval followed in the Oligocene epoch. Whatever effect it may have had on the Columbia Plateau is now largely obscured. Drysdale[3] records a post-Eocene–pre-Miocene erosion interval for the Interior Plateaus and Brooks[4] records a post-Eocene erosion interval for the Yukon Plateau. Dawson,[5] Spurr,[6] Spencer,[7] and others have correlated the peneplains thus produced as belonging to the same period, making it appear that between the close of the Eocene epoch and the beginning of the Miocene epoch there was a period of widespread peneplanation. Daly,[8] however, insists that there was no period of general peneplanation, and states that the upland surface was produced by several pre-Miocene erosion cycles. The residual mountains of British Columbia, Yukon Territory and Alaska, and the Blue Mountains of Oregon probably represent masses which remained unsubdued during this time (one or more cycles as the case may be), although they may date back to the early Tertiary or late Mesozoic erosion period.

The first basaltic flows on the Columbia Plateau are assigned to the Miocene epoch.[9] Similar flows, more localized, however,

[1] A. C. Spencer, *op. cit.*, pp. 125–28.

[2] G. O. Smith and F. C. Calkins, *U.S. Geol. Survey, Bull. 235*, pp. 85–90.

[3] C. W. Drysdale, *Geol. Survey Canada, Guide Book No. 8*, Part II, pp. 235, 236.

[4] A. H. Brooks, *op. cit.*, pp. 278, 279.

[5] G. M. Dawson, *Trans. Royal Soc. Can.*, VIII, sec. 4, p. 12.

[6] J. E. Spurr, *U.S. Geol. Survey, 18th Ann. Rept.*, Part III, p. 260.

[7] A. C. Spencer, *op. cit.*, p. 128.

[8] R. A. Daly, *Geol. Survey Canada, Guide Book No. 8*, Part II, p. 164.

[9] I. C. Russell, *op. cit.*, p. 61.

occurred at the same time on the Interior Plateaus and on the Yukon Plateau.[1]

Throughout all Tertiary time the belt of intermontane plateaus north of the Great Basin was fairly rigid.[2] However, in late Miocene time slight orogenic movements warped the early Miocene lavas into broad synclinal basins and anticlinal domes.[3] These movements were probably coincident with the profound faulting movements which affected the Great Basin. Lava flows which continued until very recent time have largely obscured the evidence of such movements on the Columbia Plateau, but they are plainly to be seen in the northern divisions.

Late in the Pliocene epoch there was a general but differential uplift of the entire Cordilleran region. This prepared for the development of the present upland surface. Dissection following this uplift marked out the main features of the present topography. The erosion cycle thus begun was halted, however, north of the Columbia Plateau by the formation of the Pleistocene ice cap. Normal processes of erosion which were renewed after the withdrawal of the ice have continued the dissection, but the topography bears the characteristic marks of glacial modification.

THE ROCKY MOUNTAIN SYSTEM

East of the Intermontane Plateaus and bordering this region throughout almost its entire length is another major division of general Alpine habit in strong topographic contrast with the plateaus. It is the most difficult of all the Cordilleran regions to name or define, because of the indefinite and varied manner in which names have been applied to it and its subdivisions.

A ruling of the United States Geographic Board makes the term "Rocky Mountain System" embrace the whole of the mountainous region between the forty-ninth parallel and the Rio Grande River. However, this definition does not harmonize with recent studies in physiographic boundaries, as it includes a large area in Texas and New Mexico of a character essentially different from that of the mountains, and excludes a large and closely related region north

[1] L. Reineke, *op. cit.*, p. 38.

[2] F. L. Ransome, *op. cit.*, p. 338. [3] C. W. Drysdale, *op. cit.*, pp. 235, 236.

of the forty-ninth parallel. Daly[1] limits the use of the term to what is really the Canadian extension of the Front Ranges of the United States and fails to recognize that the term "Rocky Mountains" is used in a very much broader sense by both popular and scientific writers in the United States. Ransome[2] applies the term "to the whole of that part of the Laramide System which extends from the Bering Sea to the southern ends of the San Juan and Sangre de Cristo ranges in Colorado." Fenneman[3] makes his Rocky Mountain division within the United States include practically the same area as Ransome's, though the latter wrote of general geology rather than physiography.

There is something to be said, of course, in favor of each of these definitions, as well as of the earlier nomenclature proposals of Dawson and Dana, more or less perhaps as one lives north or south of the forty-ninth parallel. However, in spite of all that may be written, and in the face of frequent inconsistencies, *popular usage* will always be the final arbiter in questions of geographic names, and as Ransome's and Fenneman's definition conforms more nearly to popular usage than the others it will be used in this paper.

The Canadian divisions of the Rocky Mountain System are easily correlated with the divisions lying within the United States; in fact, the so-called "Northern Rockies" of the United States and the ranges of British Columbia belong to one and the same province. This province may be further subdivided into four orographic units, separated among themselves and from adjacent provinces by five roughly parallel, structural, north-south lines, namely, (1) the western edge of the Great Plains; (2) the Rocky Mountain trench; (3) the Purcell trench; (4) the Selkirk valley; and (5) the eastern edge of the Intermontane Plateaus.[4]

The Rocky Mountain trench is a long, narrow, intermontane, structural depression or trough that extends from Flathead Lake in Montana northward almost to the boundary between British Columbia and Yukon Territory, a distance of about 990 miles.

[1] R. A. Daly, *Geol. Survey Canada, Mem. 38*, p. 27.

[2] F. L. Ransome, *Problems of American Geology*, p. 291.

[3] N. M. Fenneman, *op. cit.*, pp. 119–24 and pl. 2.

[4] R. A. Daly, *op. cit.*, p. 26.

It is occupied successively by the headwaters of the Columbia, Fraser, Peace, and Liard rivers, nearly all of which leave the trough by transverse gorges cut in the adjacent mountains.

The orographic unit lying between this trench and the western edge of the Great Plains includes the Lewis, Livingstone, Mission, and a few smaller ranges in the United States, and Daly's "Rocky Mountain System" of British Columbia and Alberta.[1] The topography of these ranges is generally bold, and elevations of more than 10,000 feet are attained by some of the peaks. These are the true *front ranges* of this part of the Rocky Mountain System.[2]

The Purcell trench is also a structural trough. It extends from Bonners Ferry, Idaho, northward in line with the courses of the Kootenay and Beaver rivers to a point about 200 miles north of the International Boundary, where it joins the Rocky Mountain trench.

The orographic unit that lies between these two trenches comprises the Coeur d'Alene, Cabinet, Flathead, and Purcell ranges. The relief is less than that of the Front Ranges. Few peaks surpass 7,500 feet, except in a part of the Cabinet Range, and on the whole only a small proportion of the summits attain 7,000 feet. The more important stream courses trend about northwest and form boundaries of the chief subdivisions, each of which bears evidence of being a dissected plateau.[3]

The Selkirk Valley, although not a structural depression, is a valley of the first rank. It is drained southward by the Columbia River, and extends from a point about 60 miles south of the International Boundary, where the river turns westward to enter the lava fields of the Columbia Plateau, to a point about 250 miles north of the boundary, where it also joins the Rocky Mountain trench.

The mountainous unit lying between the Selkirk Valley and the Purcell trench embraces Daly's Selkirk System, which in its extension south of the boundary includes the Pend d'Oreille Mountains. The topographic character of this unit is similar to that of the unit next to the east. In the southern part the mountains are generally rounded, and but few of the summits rise above 5,000 feet. North

[1] F. C. Calkins, *U.S. Geol. Survey, Bull. 384*, p. 12.

[2] Bailey Willis, *Bull. Geol. Soc. Am.*, XIII, pp. 305–52.

[3] F. C. Calkins, *loc. cit.*

of the boundary, however, they are more rugged, and in places peaks attain heights of 7,000 feet.[1]

The fourth orographic unit lies between the Selkirk Valley on the east and the edge of the Intermontane Plateaus on the west, excepting a distance of about 75 miles south of the International Boundary, where it abuts against the Cascade Mountains. It embraces Daly's Columbia System, which includes the Colville Mountains of Washington. This unit is characterized by comparatively low mountains that commonly show a certain uniformity of summit levels. Topographically they are not sharply distinguished from the mountains of the Interior Plateaus; however, there are no remnant plateaus, and they are to be regarded as a group distinct from any association with the mountains of that division.[2]

These four units form a group which writers on the physiography of the United States have frequently referred to as the "Northern Rockies." This term fails to convey a proper idea of their relative location on the continent, however, and in the absence of a better name, as well as for convenience in discussion, they will be referred to hereafter in this paper as the "Boundary Group."

Just north of the sixtieth parallel rise the Mackenzie Mountains, the greatest mountain group of Canada. This group consists of two ranges—an older range against the eastern edge of which a newer or front range has been built up. It has a crescentic axis, paralleling the general trend of the Cordilleran provinces, and extends from the valley of the Liard River to the valley of the Porcupine River. The group has a maximum width of about 300 miles. There is no well-defined crest line, and it appears to be a complex of mountain masses which are the result of deformation and erosion following an uplift.

The topography of the older western range is governed to some extent by structure, many of the wider valleys being cut in soft strata, and the higher ridges and peaks formed by uptilted hard beds. The highest peaks and most-rugged crests are built of granite stocks. The surface features in general are those which result from long-continued differential erosion acting on an uplifted and

[1] F. C. Calkins, *op. cit.*, p. 12.

[2] O. E. LeRoy, *Geol. Survey Canada, Mem. 21*, p. 23.

deformed region, somewhat modified by glaciation. Some of the higher peaks are estimated to measure 8,000 feet, but the general vertical relief is from 3,000 to 4,500 feet.

The eastern or newer range displays a marked difference in topography. Its structure is due to fracturing, buckling, and faulting, which has resulted in a more rugged and compact range of crumpled and tilted blocks. The highest peaks are roughly pyramid-shaped masses that reach elevations of 6,500 to 7,500 feet. Erosion has not reached such an advanced stage as in the western range.

Keele[1] regards the Mackenzie Mountains as closely related in both geology and structure to the Boundary Group, and, applying the various criteria used by physiographers, it would seem that this group may be definitely placed in the same classification as the Rocky Mountains.

Just beyond the boundary between Yukon Territory and Alaska another mountain group rises and extends westward toward Bering Sea. The name Endicott Mountains, originally applied to a single range of this group, is now made to include the whole.[2] Brooks[3] correlates these mountains as an orographic continuation of the Mackenzie group and as a part of the great physiographic division of the Rocky Mountain System.

The Endicott Mountains are sharply defined. They are bounded on the south by the Yukon Plateau and on the north by the Anatuvuk Plateau, a part of the Great Plains province. The southern slope rises rather abruptly from the uplands of the Yukon Plateau, though the line between the uplands and the mountains is irregular, at one point bending southward to include a spur, at another forming a deep re-entrant into the front of the range. On the Arctic slope the descent is still more abrupt. For long stretches the mountains present a bold escarpment to the north, and the sharp transition from the smooth, moss-covered (Anatuvuk) plateau to the bold, rugged mountains is very striking.

So far as is known, the Endicott Mountains embrace at least two distinct ranges. The topography is rugged and the transverse

[1] Jos. Keele, *Geol. Survey Canada, Pub. 1097*, pp. 13–18 and pl. 3.

[2] F. C. Schrader, *U.S. Geol. Survey, Prof. Paper 20.*

[3] A. H. Brooks, *op. cit.*, pp. 42–46.

valleys are sharply cut. The longitudinal valleys are broad, of gentle slopes—some of them of the basin type—and divide the group into several units. The northern or Front Range has an altitude of more than 6,000 feet, and in places peaks reach 8,000 feet. The altitude of the southern range reaches scarcely 5,000 feet. The southern range shows a remarkably even sky-line, which strongly suggests that it has been carved from a former plateau.[1]

Important topographic features that may be used in classifying all the groups herein discussed into one large major division of the North American continent are: (1) definite delimitation of each group on two sides respectively by the Great Plains and Intermontane Plateaus; (2) a high, bold "Front Range" separating the mountains from the Great Plains; (3) a range of lesser altitude and of a dissected plateau type standing behind each of the Front Ranges; and (4) a persistent *en échelon* arrangement of the Front Ranges from the Sangre de Cristo Mountains of Colorado to the Endicott Mountains of Alaska.

Within the United States the physiographic history of the Front Ranges begins with the post-Laramie deformation. This event raised the Jurassic-Cretaceous sediments into positions where they were subject to active erosion. Mature dissection of these sediments, and of the igneous bodies which had been intruded into them, of varying degrees of hardness and standing in diverse structural attitudes, has wrought the present topographic forms. The dissected plateau uplands lying west of the Front Ranges are probably remnants of a Pliocene or late Tertiary peneplain.

Schofield[2] implies a similar history for the Boundary Group, and the work of Brooks and Schrader in Alaska indicates a similar history for the Endicott Mountains. The Mackenzie group has been studied only in reconnaissance, but from what is known of its structure and stratigraphy and its relation to adjoining provinces it seems that we may be warranted in drawing the tentative deduction that it also participated in the events outlined for the United States.

[1] A. H. Brooks, *ibid.*

[2] S. J. Schofield, *Geol. Survey Canada, Guide Book No. 9*, p. 21.

[*To be continued*]

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Miller, William J. *Geology of the North Creek Quadrangle, Warren County, New York.* Bull. Univ. of the State of New York. N.Y. State Museum Bull. No. 170, 1914. Pp. 90, figs. 10, pls. 14, map. 1.

Rocks described are diabase, pegmatite, gabbro, syenite, granite, and various metamorphosed rocks. Chemical analyses and recomputations into the norm are given, as well as volumetric modal analyses for many rocks which have not been chemically analyzed. Nine varieties of reaction-rims are reported. Differentiation was found in a gabbro mass. The composition varies from syenite to gabbro in the same mass, but the different phases are irregularly distributed and seem to follow no law. Contact phenomena are described, and the volumetric composition of the rock, which varies from typical gabbro to typical granite, is given for nine different zones.

The geological history of the region is told and a few pages are devoted to economic geology.

Miller, William J. "Magmatic Differentiation and Assimilation in the Adirondack Region," *Bull. Geol. Soc. Amer.*, XXV (1914), 243–64.

The writer describes the effects of the intrusion of great masses of syenite and granite in the Grenville rocks of the Adirondack region. He cites the older literature with regard to the differentiation in this region and shows, by his personal observations, that the inclusions of rocks of the Grenville series, varying from a few feet to a few rods in length, have been either partially or wholly fused and melted into the granite or syenite. While the author believes that stoping and engulfment of portions of the Grenville series was a common process in this region, he says that there is no positive evidence that the composition of the igneous intrusive was thereby appreciably changed.

MILLER, WILLIAM J. *Geology of the Lake Pleasant Quadrangle, Hamilton County, New York.* Bull. 182, New York State Museum, 1916. Pp. 75, pls. 10, figs. 4, map 1.

Geologic and physiographic history of the region, together with petrographic descriptions of various anorthosite-gabbros, syenites, granites, granite- and syenite-porphyries, gabbros, and diabases.

MOSES, A. J. "A Scheme for Utilizing the Polarizing Microscope in the Determination of Minerals of Non-Metallic Lustre," *School Mines Quart.*, XXXIV (1913), No. 4, pp. 30.

A very useful series of tests which may be applied to the determination of minerals as a supplement to the usual tests before the blowpipe, etc. After describing the general methods of procedure, the writer gives a 19-page key based on taste, flame-color, fusibility, and effervescence or gelatinization with acid, and final optical tests based on refractive index, interference color, optical character, and miscellaneous characteristics.

NIGGLI, PAUL. "The Phenomena of Equilibria between Silica and the Alkali Carbonates," *Jour. Amer. Chem. Soc.*, XXXV (1913), 1693–1727.

O'NEILL, J. J. *St. Hilaire (Beloeil) and Rougemont Mountains, Quebec.* Canada Dept. Mines, Mem. 43, Geol. Series 36, Ottawa, 1914. Pp. 108, map 1, bibliography.

Rising out of the plain to the east of Montreal is a series of isolated hills representing volcanic necks or laccoliths. They have been called the Monteregian Hills and may be tabulated as shown on page 188.

After giving a short account of the geology of the whole region, the author takes up the structural features of St. Hilaire and Rougemont mountains, and concludes from the evidence of undisturbed country-rock, of the coarse texture of the igneous mass close to the outer contact, of the vertical conduit through which the magma passed, of the development of flow texture in the essexite, and of the brecciation shown in the syenite at the contact, that St. Hilaire is an eroded volcanic neck. The evidence at Rougemont Mountain is not so positive. The coarse texture at the contact, which is wavy without regard to topography, and the cliff development on two sides seem to indicate that the conduit was

practically vertical. It therefore probably also represents an eroded volcanic neck.

Mountains in Order from East to West	Main Intrusion in Each in Order of Occurrence			Nature of Intrusion	Described by	Area in Sq. Miles
	No. 1	No. 2	No. 3			
Shefford......	Essexite	Nordmarkite	Pulaskite	Laccolith	Dresser	9.0
Brome.......	Essexite to theralite	Nordmarkite to nephelite syenite, and dikes	Tinguaite	Laccolith	Dresser	30.0
Yamaska.....	Yamaskite to essexite to akerite	....	....	Neck	Young	5.5
Rougemont...	Yamaskite to essexite to rougemontite	....	....	Neck	O'Neill	9.5
Johnson......	Essexite to pulaskite	....	....	Neck	Adams	0.77
St. Hilaire....	Essexite to rouvillite	Nephelite-syenite	....	Neck	O'Neill	6.76
St. Bruno....	Essexite to syenite (umptekite)	....	....	Laccolith?	Dresser	2.83
Mount Royal.	Essexite	Nephelite-syenite	....	Neck? Laccolith?	Adams Buchan	2.0

The rocks of St. Hilaire are essexite and nephelite-sodalite-syenite, with several varieties of each, and there are various dikes. Essexite was first intruded. At various places in it, brown hornblende becomes prominent. In one occurrence there is a very small amount of ferromagnesian mineral, and labradorite and nephelite greatly predominate. It is proposed to call this variety *rouvillite.* Its mode, determined by calculation based on measurements by the Rosiwal (invariably spelled Rosiwald in the report) method is, plagioclase (Ab_1An_1 to Ab_1An_4) 56 per cent, nephelite 19.5 per cent, purplish augite 7.0 per cent, hornblende 3.5 per cent, pyrite 2.5 per cent, apatite 1 per cent. The rock actually is a light-colored theralite, with a ratio of light minerals to dark of 85 to 15.

On Mount Rougemont an anorthite-olivine-gabbro occurs. It consists by volume of anorthite 52 per cent, augite 32.5 per cent, olivine 8.5 per cent, iron ore 6.5 per cent, hornblende 0.5 per cent. For this rock the name *rougemontite* is proposed.

The author suggests the probability that the Monteregian region may be part of a larger province, and the rocks may be related to the anorthosites.

Numerous analyses and recalculations into the C.I.P.W. system, as well as volumetric determinations by the Rosiwal method, are given.

Reviews

Yearbook for 1910. Illinois State Geol. Survey, Bull. No. 20, 1915. Pp. 165, pls. 14, figs. 8.

Besides the administrative report and mineral production statistics, this bulletin contains five papers of geologic interest. These reports are based on work done in co-operation with the U. S. Geological Survey.

The report of F. H. Kay on the Carlinville oil and gas field and of E. W. Shaw on the Carlyle oil field were prepared in 1911, when those fields were being developed. Both are located in south central Illinois. The rocks are monoclinal, eastward-dipping Mississippian and Pennsylvanian strata covered by glacial drift. Minor irregularities of structure determine the location of the oil pools. The Carlyle oil sands are in the upper Chester; those at Carlinville near the base of the Coal Measures. The production of both fields has decreased rapidly since 1912.

The report of E. T. Savage on the geology and mineral resources of the Springfield quadrangle appeared, in abbreviated form, as Folio 188 of the U.S. Geological Survey.

S. W. Parr contributes a paper on the valuation of coal for gas manufacture.

E. W. Shaw describes extinct Pleistocene lakes in the valleys of tributaries of the Ohio and Mississippi. The mouths of certain tributaries were dammed by aggradation by the master-streams. The deposits subsequently deposited in the ponded waters thin out upstream. The older of the lake beds are slightly younger than the Illinois till; later deposits are of Wisconsin age.

H. R. B.

Mississippi, Its Geology, Geography, Soils, and Mineral Resources. By E. N. Lowe. Miss. State Geol. Survey, Bull. No. 12, 1915. Pp. 335, pls. 28.

This volume is unique among recent state geological survey reports. The bulletin was prepared as a non-technical summary of the geology, geography, mineral resources, underground waters, and soils of the state. By the introduction of preliminary chapters treating of geologic processes, it becomes an elementary geologic textbook for the people of

Mississippi. It is admirably adapted to the needs of teachers and could well be made the basis of a practical and interesting first course in geology.

Mississippi is particularly fortunate in the publication of a report such as Mr. Lowe has prepared. It deserves a wide circulation among the people of that state.

H. R. B.

Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. By. W. H. Emmons and F. C. Calkins. U.S. Geol. Survey, Prof. Paper 78, 1915. Pp. 271, pls. 17, figs. 55.

The Philipsburg quadrangle includes an area of 827 square miles lying immediately west and northwest of Anaconda, Montana. It is a country of strong relief, almost midway between the eastern and western divisions of the Rocky Mountains. The geologic section includes formations ranging in age from Algonkian to Recent. The Belt series, the oldest rocks in the area, is divided on lithologic grounds into six formations. Their total thickness is 15,000 feet. Next above and separated from the Belt series by a striking unconformity is the Cambrian system, comprising the Flathead, Silver Hill, Hasmark, and Red Lion formations. The Red Lion contains Upper Cambrian fossils. It is overlain by the Maywood formation, of doubtful Silurian age. The Devonian is represented only by the Jefferson limestone; the Mississippian by the Madison limestone; the Pennsylvanian by the Quadrant formation. Though the stratigraphic relations of the Paleozoic systems was not clearly made out, each is probably set off by disconformities.

The Mesozoic is not strongly developed in this part of Montana. Only three formations are here present—the Ellis, Kootenai, and Colorado. The early Tertiary was marked by powerful crustal movements. The pre-Tertiary sediments were complexly folded and overthrust and extensive igneous masses were intruded. Later the region was the scene of two epochs of vulcanism. Certain gravel deposits contain Miocene vertebrates. The Tertiary closed with tilting and a general uplift. During Pleistocene time there were at least two stages of Alpine glaciation.

The early Tertiary batholiths and smaller intrusives are granites, granodiorites, and diorites, with associated pegmatites, aplites, and lamprophyres. At and near their contacts with these intrusives the sediments are notably altered. The pneumatolytic solutions that effected these changes are believed to have carried chlorine, fluorine,

boron, iron, soda, and silica. Recrystallization cannot be relied upon as the sole explanation of the observed development of silicates and other contact minerals; they are due in part to a transfer from magmatic sources. The ores of the district are genetically related to the intrusives, their deposition representing the closing stage of igneous activity.

The first discovery of placer gold in Montana was made within the Philipsburg quadrangle in 1852. The gravels have yielded something less than $2,000,000. The total production of the underground mines, developed later, is about $50,000,000. Of this amount one-fifth is gold, the remainder silver. The deposits are of three types: fissure veins cutting both igneous and sedimentary rocks, contact metamorphic replacement deposits in limestone near the granite intrusives, and replacement deposits in sedimentary rocks.

Silver-bearing veins in granite are of principal importance, the Granite-Bimetallic mines having yielded $32,000,000. The veins follow strong, sharply defined fissures. The wall rock shows strong hydrothermal alteration of the sericite-calcite type. The primary ore has a gangue of quartz, calcite, and rhodochrosite inclosing sulphides—pyrite, stibnite, tetrahedrite, tennantite, galena, arsenopyrite, and sphalerite. Later the veins were fractured and refilled with calcite and rhodochrosite. Secondary sulphides, chiefly pyrargyrite, are conspicuously developed between the 300- and 800-foot levels. Oxidized ores containing cerargyrite, pyromorphite, and native silver occur above this zone.

At the Cable mine a contact metamorphic gold copper ore occurs in a tabular mass of limestone surrounded by granodiorite. The ore replaces limestone and consists of coarse calcite and quartz with pyrite, pyrrhotite, arsenopyrite, magnetite, and gold. The typical ore is not an intergrowth with heavy contact silicates. Those minerals formed before the principal ore deposition began.

Gold-bearing replacement veins in limestones near intrusive contacts form a transitional type. The minerals of the ore are quartz, calcite, siderite, and some pyrrhotite, magnetite, and specularite. Pyrite is the principal auriferous mineral.

This report deserves a high place among recent economic papers.

H. R. B.

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DIASTROPHISM AND THE FORMATIVE PROCESSES. IX[1]

A SPECIFIC MODE OF SELF-PROMOTION OF PERIODIC DIASTROPHISM

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In the opinion of many students of diastrophism, world-wide deformative movements tend toward periodicity in the very nature of the case; more or less oscillation between relatively active and quiescent stages would arise without any special aid from accessory agencies. But in the natural order of things secondary movements often spring from the primary actions and abet them. It is the purpose of this note to call attention to a specific form of secondary action by which the oscillations between the active phases of deformation and the intervening quiescent stages are accentuated and the periodicity of major diastrophism emphasized.

When world-wide diastrophism follows a period of general base-leveling and wide sea-transgression the diastrophic movement is logically regarded as springing from accumulated earth-stresses of such a nature as to give rise to relative downward movements of the sub-oceanic segments and relative upward movements in the continents in spite of whatever burden of epicontinental waters

[1] For previous article (Part VIII) of this series see the *Journal of Geology* for July-August, 1914.

the latter may bear. The spontaneous transfer of the epicontinental waters to the ocean basins, thereby unloading the continents and further loading the basins, adds force to the diastrophic process and constitutes a specific example of self-instituted promotion of periodicity. The periodicity is emphasized because this action tends to push the diastrophic movements beyond what would otherwise have been their limits, and this results in an enhanced degree of easement of the original body-stresses and by so doing more effectively prepares the way for a new period of quiescence, base-leveling, and sea-transgression.

This will become quite clear by following in detail the history of a typical case, if the interpretation is guided by that phase of the doctrine of periodic diastrophism which is specifically appropriate to a solid elastico-rigid earth. In strict consistency with such an earth isostatic readjustments are assumed to take place by wedging and not by undertow beneath a floating crust. This type of isostatic adjustment is analogous to the familiar balancing of weight against weight on a pair of scales and is clearly distinguishable in mode, though not in principle, from the more common concept of flotation which has for its analogue the hydrometer.

1. Let it be assumed that the continental platforms, including the sea shelves, occupy one-third of the earth's surface and the true ocean basins—neglecting the continental shelves—the remaining two-thirds. For a typical stage from which to start let it be supposed that as the result of a general diastrophic movement the oceans have recently been withdrawn into the abysmal basins so that the whole surface of the continental platforms, including the continental shelves, shall have become land and the terrace edge of the shelf shall coincide with the oceanic shore line. Some such condition seems to have been realized in late Tertiary times. To add concreteness let the mean measure of continental protrusion above the lowered sea-level, including the shelf depth, be 900 m. and the mean abysmal depth 5,000 m.

2. Now let a typical period of relative freedom from general diastrophic movement ensue. Such relatively quiescent periods are implied by general base-leveling and wide sea-transgression. Their periodic recurrence seems to be substantiated by the great

overmantlings of large fractions of the face of the continents by marine deposits in Ordovician, Silurian, Cretaceous, Eocene, and other periods. Without such relatively static periods general base-leveling seems impossible. Theoretically such periods are assignable to previous effective easement of all differential stresses of the higher order. Such easement is really implied in the emergent state of the continents and the reciprocal depressed state of the great basins just assumed as the first stage in the case we are following.

3. During this relatively quiescent period let the normal processes of denudation and deposition follow their inevitable courses, unloading the continents and loading the ocean basins, while the sea slowly encroaches upon the borders of the continental platforms until, let us say, 30 per cent or 40 per cent of the surface of the continental platforms is overlipped by the thin edges of the oceans. Among the incidents of this period the following may be noted:

a) In the early stages the bordering belts of the continents, as a rule, suffered greater relative unloading than the interiors because they had been most affected, on the average, by the preceding diastrophism, and their drainage gradients were higher than those of the more remote interior and the denudation more rapid, while the direct action of the cutting edge of the sea added its effects.

b) Later in the period, as the sea crept forward over the widening shelf and gave rise to the deposition of top-set beds upon the surface of the shelf, the weight of these deposits compensated in some measure for the previous unloading, while the rise of the sea-level itself, due to the sediment carried into the oceans, added some further compensation by an increasing burden of sea-water.

c) The mechanical sediments from the land, beside lodging on the sea-shelf as top-set beds, accumulated predominantly around the shelf-edge as fore-set beds, while subordinately they were carried farther out to sea and settled widely over the ocean bottom.

d) The solvent material was at first distributed by currents and diffusion with approximate uniformity throughout the oceanic waters, but later a part of it was extracted by organic and other agencies and deposited wherever chance overtook it, often far from its point of origin on the continent.

It is worth observing that the highly carbonated state of the abysmal and polar waters of the present subglacial period leads to a large measure of solution of the calcareous relics that fall from the pelagic plankton toward the abysmal depths, and this greatly limits current oceanic deposits; but this specially solvent state of the abysmal waters probably did not obtain during the mild climates typical of times of wide sea-transgression. Hence a wider and thicker abysmal deposit may be postulated for those times.

4. Now at a critical stage of this progress when 30 per cent or 40 per cent of the surface of the continental platforms had become covered by the transgressing shelf-seas, let it be assumed that the loading and unloading had developed sufficient differential stresses in the earth-body to start easement movements by the depression of the weighted suboceanic segments on the one hand and the relative elevation of the denuded continental segments on the other. These reciprocal movements would be followed by a flow of water from the rising continental shelves to the sinking ocean basins. This shift of burden from one side of the equation to the other would tend to intensify the diastrophic movement. If this new emergence returns to a stage comparable with that assumed at the outset, all the water-burden upon the sea-shelf, a matter of perhaps 300 lbs. or so per square inch, averaged for the whole shelf area, will have been transferred in this unrestrained way to the abysmal basins, where it will be an added burden of equal value, though much more widely and uniformly distributed. In more general terms this may amount to a mean unburdening of the continental area, considered as a whole, to the extent of about 50 lbs. per square inch and a simultaneous mean loading of the whole oceanic area of about 25 lbs. per square inch.

A concurrent enhancement of effect will arise from the ease with which the rock mantle accumulated during the base-leveling stage—as well as the soft sediments on the face of the sea-shelf—will be eroded and carried down to the borders of the depressed ocean as the continental elevation advances.

It thus appears that such a general diastrophic movement, in the course of its own normal line of action, brings into play an easy and prompt shifting of load of a special type that tends to acceler-

ate the primary movement and give it a cumulative value. This tends to push the movement to a maximum the better to prepare the way for a new quiescent period.

Such cumulative periodicity, both primary and enhanced, seems not only consistent with a solid elastic earth but an inevitable consequence of the elastic rigidity of such an earth. As already remarked, the normal mode of isostatic adjustment in such an earth is thought to be wedging action in the form of movements on the part of its constituent tapering prisms, conical, pyramidal, or otherwise, in response to the varying stresses imposed on them. Facilities for such movements are presumed to be provided by vertical schistosity developed in the tracts where the differential stresses are greatest, and by the very stresses that actuate the deep diastrophic movements. So originated they should reach to whatever depths may be seriously affected by differential stresses of an order requiring readjustment. No undertow in a hypothetical mobile substratum is necessarily involved and none is postulated. The weighted parts wedge down and the unloaded parts are wedged up until the differential gravitative stresses are essentially equated and an isostatic state reached. Movement in a rigid earth of course is not presumed to take place until stresses have accumulated to a degree adequate to force it and hence the relatively quiescent stages. The quiescent stages occupied in such stress-accumulation are interpreted as constituting the periods marked by base-leveling and sea-transgression, appropriate conditions for which are thus provided. General isostatic readjustments are of course interpreted as synonymous with general diastrophic movements and so are regarded as equally periodic. As the present epoch has been preceded by great diastrophic movements, the earth body is presumably now in a stage of approximate isostatic adjustment, as implied by geodetic evidences.

CORAL REEFS AND SUBMARINE BANKS

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PART I

Two contrasted theories of coral reefs.—As the coral-reef problem stands at present, consideration may be given chiefly to Darwin's theory of intermittent subsidence and to the new glacial-control theory as presented by Daly; for the latter seems according to

Vaughan's latest statement to include the essential features of his theory of submerged platforms. All other theories are excluded because they fail to take account of the submergence by which the central islands or continental masses within barrier reefs have gained their embayed shore lines while the reefs grew up around them; by which fringing reefs and many elevated reefs have gained their unconformable contact with the eroded slopes that they rest upon; and by which, therefore, the formation of atolls also has probably been controlled. Hence it is desirable to examine with especial care the fundamental postulates and processes and the essential consequences of the two surviving theories with the object of making unprejudiced choice between them. Let it be noted, however, that while certain essential postulates of the two theories are mutually contradictory and while the conditions involved in them are very unlike, the processes of the two theories are by no means mutually exclusive; they may work together. This is particularly true regarding the intermittent subsidences and occasional uplifts of Darwin's theory and the climatic oscillations of ocean-level of the glacial-control theory; their combined action deserves careful consideration as affording a closer approach to the conditions under which reefs have been formed than is provided by Darwin's theory alone; and herein lies, to my mind, the chief value of the glacial-control theory. It is therefore unfortunate that so much emphasis has been placed in the latest presentation of the glacial-control theory upon the fundamental postulate of long-continued stability of the earth's crust in those large parts of the Pacific and Indian oceans that are characterized by atolls, and upon the secondary postulate that the submergence during which reef upgrowth has taken place in those regions is due wholly to the postglacial rise of the ocean surface by about 240 feet; for the newest theory of coral reefs is thereby brought into unnecessary opposition to Darwin's theory.

It is my desire to make the following discussion as objective and impartial as possible, and to exclude from it all suggestion of the "warfare of scientific theories" which some of my contemporaries seem to think is necessarily involved in the competitive search for the true explanation of a scientific problem; for it happens

curiously enough that, of the very few persons in this country who are now actively interested in the coral-reef problem, the two—Professor Daly and myself—who are especially concerned in the present discussion are long-time friends, present-day colleagues, and next-door neighbors. We have the same object in view, although our judgments differ as to the weight to be attached to various factors of our problem. We believe that our common object will be best reached through the open exposition of the many considerations that guide our opinions; and I for my part should be well satisfied if the competent critics who have admired the ingenuity with which Daly has set forth the possibilities of the glacial-control theory and who have been impressed by the strength that it has gained through his earnest advocacy should find in the following pages a fair comparison of its possibilities with those of Darwin's theory.

Plan of discussion.—The plan of discussion is as follows: The chief postulates of the two theories regarding subsidence and stability will first be examined in order to make clear the strong contrasts between them. The reef structures consequent upon the postulates and processes of the two theories will then be deduced in order to discover the nature of the evidence that each theory demands for its support. Brief consideration will be given to the possible destruction of coral reefs during the glacial period as assumed by the glacial-control theory, with special attention to the evidence from Hawaii, Tahiti, and Murea; the conclusion is thus reached that reefs as a rule survived the epochs of glacial cooling, and hence that preglacial reefs were not abraded by the glacial ocean. The flatness of atoll-lagoon floors and the similarity of their depths will next be examined in order to learn whether the explanation of these features demands the truncation of preglacial islands by the waves of the lowered glacial ocean or whether they may be accounted for by aggradation during intermittent subsidence; the bearings of the exterior profile and the volume of existing reefs on the same question will also be inquired into; all with the result of showing that stability of reef foundations is not essential in accounting for these features, because they can also be accounted for as a result of subsidence. The submarine banks

or so-called "drowned atolls" of the coral seas are next reviewed, first as to the necessity of abrasion instead of aggradation for their production and secondly as to the probability of their having stood still, as preglacial volcanic islands, long enough to be worn down and more or less abraded instead of having suffered intermittent subsidence. Both of these questions are answered in favor of Darwin's theory; thus these banks give less evidence for the glacial-control theory than has been claimed for them. Extra-tropical banks, where abrasion is attested by the clift shores of the residual islands, are then compared with the banks of the coral seas, where abrasion is hypothetical: it thus appears probable that the lowering of the ocean during the glacial period was much less than 40 fathoms.

The general result of the discussion is that the long-enduring stability of reef foundations and the abrasion of reefs and islands by the chilled and lowered ocean of the glacial period are, to say the least, extremely improbable; and therefore that coral reefs are better explained by subsidence and aggradation than by stability and abrasion; and further that subsidence of considerable amounts has probably combined with changes of ocean-level of small amounts in determining the conditions under which the sea-level reefs of today have been formed.

Intermittent subsidence as postulated in Darwin's theory.—The degree of opposition between the two theories here to be discussed may be learned by citing a number of pertinent passages from the original expositions by their authors. Darwin found warrant for the postulate of subsidence in his geological researches, which gave "every reason for believing that there are now large areas gradually sinking, in the same manner as others are rising. . . . . When we consider how many parts of the surface of the globe have been elevated within recent geological epochs, we must admit that there have been subsidences on a corresponding scale, for otherwise the whole globe would have swollen (*Structure and Origin of Coral Reefs*, 1842, p. 95).[1] Since the voyage of the "Beagle" a larger knowledge of the earth's history has been gained, as a result of

[1] Additional citations from Darwin's *Structure and Origin of Coral Reefs* will be given by page numbers only.

which some geologists have doubted the occurrence of important subsidences in the ocean beds during later geological times; but Darwin's opinion is re-enforced by the conclusions reached by other geologists: for example, Schuchert has recently summarized the results of his study of a large oceanic region as follows: "The entire western half of the Pacific bottom, and especially the Australasian region, appears to be as mobile as any of the continents of the Northern Hemisphere, with the difference that the sum of the continental movements is upward, while that of the ocean bottom is downward."[1] Additional re-enforcement is found in Crampton's conclusions based on the study of land snails in the Society Islands: "The evidence tends to prove that the dominant process in the South Pacific has been one of subsidence, which has progressively isolated various mountain ranges previously connected, so that they have become separate island masses, which in their turn have been subsequently converted into the disconnected islands of the several groups."[2] In view of these conclusions, independently reached by researches of different kinds, it is to my reading unwarranted to assume "a long period of nearly perfect stability for the general ocean floor." Such an assumption fully deserves provisional consideration as an abstract possibility, but it does not merit the rank of an accepted postulate from which a long sequence of consequences can be safely deduced.

Darwin's views as to the manner in which subsidence acted deserve attention. He first pointed out that the existence of many widely separated reefs is "quite inexplicable, excepting on the theory that the bases on which the reefs first became attached slowly and successively sank beneath the level of the sea, whilst the corals continued to grow upward" (98); but on the next page two variations are introduced: first, by recognizing possible changes of rate of subsidence in the phrase, "as the island sinks down, either a few feet at a time or quite insensibly," and secondly, by adverting to the probable occurrence of still-stand

[1] C. Schuchert, "The Problem of Continental Fracturing and Disastrophism in Oceanica," *Amer. Jour. Sci.*, XLII (1916), 91–105; see p. 105.

[2] H. E. Crampton, "Studies in the Variation Distribution, and Evolution of the Genus *Partula* . . . . ," Carnegie Institution of Washington, 1916, p. 12.

pauses in the phrase, "the lagoon channel will be deeper or shallower, in proportion to . . . . the accumulation of sediment . . . . also, to the rate of subsidence and the length of the intervening stationary periods." He later distinguished the consequences of recent and of ancient subsidences, and thus recognized that they need not be everywhere contemporaneous, illustrating the first case by the island of Vanikoro, in the Santa Cruz group of the Western Pacific, where "the unusual depth of the channel [lagoon] between the shore and the [barrier] reef, the almost entire absence of islands on the reef, its wall-like structure on the inner side, and the small quantity of low alluvial land at the foot of the mountains [in the encircled island], all seem to show that this island has not remained long at its present level, with the lagoon channel subjected to the accumulation of sediments, and the reef to the wear and tear of the breakers"; and then illustrating the second case by certain members of the Society group, "where . . . . the shoalness of the lagoon channels round some of the islands, the number of islets formed on the reefs of others, and the broad belt of low land at the foot of the mountains indicate that, although there must have been great subsidence to have produced the barrier reefs, there has since elapsed a long stationary period" (128). Outgrowth during a supposed stationary period was called upon to explain the broad reefs of Christmas atoll, in the Central Pacific (74), and of Diego Garcia, in the Indian Ocean (70); and the widened phase of reef development resulting from the transformation of a narrow young reef into a mature reef plain during a time of no sinking was clearly foreshadowed in the statement that "an old fringing reef, which had extended itself a little on a basis of its own formation, would hardly be distinguished from a barrier reef, produced by a small amount of subsidence, and with its lagoon channel nearly filled up with sediment during a long stationary period" (102).

To these well-considered statements another was soon added, for the conclusion to which Darwin was finally led was that "the islands in the Low Archipelago [Paumotus] have, like the Society Islands, remained at a stationary level for a long period; and this is probably the ordinary course of events, subsidence supervening

after long intervals of rest" (130). Because of the frequent repetition of this conception we might well speak of Darwin's "theory of intermittent subsidence," and not simply of the "theory of subsidence." This is well warranted by a striking passage in which it is suggested that atoll reefs "would present a totally different appearance from what they do now" if they had long remained stationary, and that "some renovating agency (namely subsidence) comes into play at intervals, and perpetuates their original structure" (31).

Insufficient attention has been given to intermittent subsidence as the basis of Darwin's theory, though he often alluded to it. He considered the possibility that an atoll might "be carried down by a more rapid movement . . . . after a subsidence of . . . . very slow nature" (104); and he wrote of "progressive subsidences, perhaps at some periods more rapid than at others" (107); of "repeated subsidences" in the supposed development of the Maldives (110); of groups of atolls growing upward "at each sinking of the land" (126); and he clearly recognized the possibility of subsidence at a faster rate than reef upgrowth, not only in the account of certain submarine banks which he interpreted as submerged atolls, but also in a rarely quoted explanation of certain fringing reefs. On the first point he wrote: "There is nothing improbable in the death . . . . from the subsidence being great or sudden, of the corals on the whole, or on portions of some of the atolls" (108); also that "through further subsidence and with the accumulation of sediment, modified by the force of ocean currents," drowned atolls might "pass into level banks with scarcely any distinguishing character" (114). On the second point the following important statement is made: "If during the prolonged subsidence of a shore, coral reefs grow for the first time on it, or if an old barrier reef were destroyed and submerged and new reefs became attached to the land, these would necessarily at first belong to the fringing class" (124). Such fringing reefs should be regarded as of a new generation; examples of them will be given in the next section. The possibility of intermittent elevation as well as intermittent subsidence was also recognized by Darwin (145, 146); and mention is made of "elevation having

succeeded subsidence" in the Friendly or Tonga group, and of "subsidence having probably succeeded recent elevation" in the Harvey or Cook group (140). Finally Darwin expressed the general opinion: "It has already been shown (and it is, perhaps, the most interesting conclusion in this volume) that the movements [of subsidence] must either have been uniform and exceedingly slow, or have been effected by small steps, separated from each other by long intervals of time" (145).

Structural features of reefs formed during subsidence.—The formation of coral reefs along recently uplifted coasts or around young volcanoes is improbable, because the loose detritus which prevails on the shore belts of such coasts is unfavorable to coral

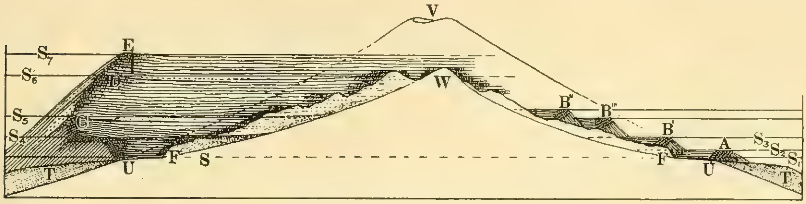


FIG. 1.—Structure of coral reef formed around a volcanic island by subsidence

growth. In the absence of reefs, coasts of these kinds will, while their slopes are dissected by streams, be attacked and cut back by the sea, except where the deltas of large rivers are built forward; as long as no change of level takes place, beach detritus will be spread along the shore and reef growth will be prevented. But if subsidence occurs, the dissected coast will be embayed; detritus will then be held in the embayments and reef growth may begin on the rocky headlands or on bare ledges off shore.[1] The longer the subsidence continues at a moderate rate the thicker the reefs will become. The essential structural features of reefs thus formed around a volcanic island are represented in Fig. 1, in which *UVU* is the initial cone, formed by eruption, with sea-level at S_1, and *UWU* is the dissected and clift cone at the time when subsidence begins; *TT* represents the ring of detritus swept off shore. Reunion, a clift and almost reefless island in the Indian Ocean, represents this stage.

[1] See "Clift Islands in the Coral Seas," *Proc. Nat. Acad. Sci.*, II (1916), 284–88.

Reef A, formed when the island has subsided so that sea-level is S_2, is a barrier of moderate thickness; the cliffs, F, previously cut, are not yet wholly submerged and the embayments are small. Tahiti, the largest of the Society Islands, is clift and encircled by reefs which are, I believe, of this kind; the submergence that prompted their formation might at first thought be ascribed to a rise of sea-level due to climatic change or to an upheaval of the ocean bottom elsewhere while Tahiti stood still; but in that case neighboring islands should show similar features, and as they do not the submergence of Tahiti as well as of its neighbors is reasonably ascribed chiefly to subsidence.

Reef B' is an unconformable fringe formed after greater subsidence rapidly accomplished; it surrounds the eroded and embayed coast of a well-dissected, but not clift, island; and it surmounts the previously formed reef, which is now a submarine bank; such a fringe should therefore be taken to represent a young reef of a new generation formed after a rapid subsidence had drowned a previously formed barrier reef in the manner suggested by Darwin. Palawan, the southwesternmost of the Philippines, has a strongly embayed western coast fronted by a broad, submerged bank, but practically without fringing reefs even around its tapering, non-clift, spur ends; thus it seems to have recently and rapidly submerged. Fauro, a small and greatly eroded volcanic island in the Solomon group, seems to have an unconformable fringing reef like B'; the submarine bank has depths of from 50 to 70 fathoms, and has a width of several miles; discontinuous reefs rise on parts of its margin, but seldom reach the surface of the sea. The granitic islands of the Seychelles have similar fringing reefs of a second generation. As the depth of the Fauro bank is greater than the climatic changes of level during the glacial period, as the amount of erosion that the volcanic mass has suffered below present sea-level appears to be much greater than could have been accomplished during the lower stands of the ocean in the glacial period, and as neighboring islands do not present similar features, the opportunity for the formation of the Fauro fringe above the submerged bank must be ascribed chiefly to local subsidence.

Reef C, with sea-level at S_5, on the left side of the diagram is a barrier of greater thickness as a result of greater subsidence; its lagoon is of greater breadth than that of reef A or B', and the embayments of its central island are strongly developed. Detrital deltas unconformably fill the embayment heads, and fringing reefs grow unconformably around the intervening spur ends. Borabora in the Society Islands has a barrier reef essentially of this kind, in which the surviving central mountain is greatly reduced from its initial form, and in which wide embayments enter between outspread spurs; the amount of subaërial erosion that must have taken place below present sea-level in order to reduce an initial cone to the existing mountainous form of this island is, in my judgment, far greater, both in depth and in volume, than could have been accomplished during the glacial epochs of lowered sea-level; hence the submergence inferred for this island should be ascribed chiefly to subsidence.

If a pause occurred during the subsidence by which reef C was formed, so that sea-level remained at S_4 for a considerable period, the reef would grow outward on its own talus—this process having been distinctly recognized by Darwin, though it is usually credited to Murray: at the same time the lagoon would be shoaled or filled and thus a narrow young reef would be converted into a mature reef plain. Yap, in the Caroline Islands of the North Pacific, has a reef plain one or two miles in width interrupted by transverse channels, but without a lagoon proper.

Reef D is an almost-atoll, in which only two small central volcanic knobs remain above water in the center of a broad and relatively shallow lagoon. Truk (Hogoleu), in the Caroline Islands, and the Gambier Islands, southeast of the Paumotus, represent this stage. Maré, one of the Loyalty Islands, north of New Caledonia, was formerly an atoll in which a small volcanic knob was just submerged in the lagoon waters; the atoll is now elevated so that the broad lagoon plain, about 20 miles in diameter with the low volcanic knob near its center, stands 200 feet above sea-level and the reef rim rises some 50 feet higher. The knob has a gentle slope and shows no signs of cliffs, hence it cannot be regarded as a

residual stack surmounting a platform of marine abrasion; it is of dense volcanic rock, hence it probably represents a well-denuded volcanic summit on which the surrounding lagoon limestones rest unconformably. If the buried volcanic slope be such as prevails in the dissected islands of the Fiji group, the thickness of the Maré reef at the margin must be 5,000 feet or more. The volume of limestone thus accumulated is truly formidable; but if the theory of subsidence be proved correct on other grounds, we can hardly object to it because it involves large quantities.

Reef *E* is a true atoll, like Funafuti, in which no volcanic central knob is to be seen. The upgrowing reef is here shown as slanting more and more inward, the longer its exterior talus becomes, for reasons that I have elsewhere set forth.[1] So long as an atoll remains at sea-level it is impossible to determine whether its structure accords with the demands of Darwin's theory or of any other theory. Penetration of its structure by boring is difficult; the boring at Funafuti, 1,114 feet deep, was made on the marginal reef; it is shown in true proportion to the diameter of the atoll by the vertical line at *E*:[2] a boring near the lagoon center would, according to the subsidence theory, have been much more likely to reach a volcanic foundation; and such a boring at Bermuda reached volcanic rock at a depth of 245 feet below sea-level and penetrated it for 1,033 feet farther: several such borings would be needed to demonstrate the form of the buried volcanic mass, as is further noted below.

If a long stationary period should supervene in the history of an atoll, its lagoon would be gradually filled and converted into what may be called an atoll plain; if such an atoll plain should suddenly subside, narrow young reefs would grow up from its surface in such a manner as to suggest the independent origin of the two forms. In so far as the Maldives offer examples of this kind their

[1] "Extinguished and Resurgent Coral Reefs," *Proc. Nat. Acad. Sci.*, II (1916), pp. 466–71.

[2] As drawn in Fig. 1, the boring passes from the true reef into the lagoon deposits, because the upgrowth of the reef is here inclined inward; if the boring had penetrated such a reef as *C*, it would have remained for its whole depth in the reef proper; if it had penetrated a horizontal or outslanting reef, like the lower part of reef *C*, it would have passed through the reef into the underlying talus deposits.

explanation by the subsidence theory evidently demands precisely the "ordinary course of events" postulated by Darwin, namely, subsidence after a long interval of rest. But let it be at once added that the glacial-control theory here supplements Darwin's theory in an effective manner by calling attention to the glacial oscillations of ocean-level, for a lowering of the ocean surface combined with a subsidence of reef foundations will produce the equivalent of a "stationary period," and a later rise of ocean-level combined with continued subsidence will cause an unusually rapid submergence; thus the apparent discontinuity of origin between a submerged atoll plain and the narrow young reefs that surmount it finds an explanation that is especially applicable to postglacial time. This aspect of the problem is referred to again below.

If sudden submergence, such as that which separated the formation of reefs *A* and *B′*, take place after the formation of atoll *E*, its upgrowth will not be continued; it then becomes a drowned atoll, of which Chagos bank in the Southern Indian Ocean, and the Macclesfield bank in the China Sea, may be examples. But it is singular that no banks of this kind are known with a greater depth than 60 or 70 fathoms; this aspect of the problem is especially considered in later sections.

In all the reefs shown in section in Fig. 1, three different structures are to be distinguished: first, the reef proper, composed in part of coral and other shallow-water organisms in place, as well as of disorderly masses of coral and much fine detritus; second, the exterior talus, pitching steeply to deep water and composed of coarse and fine detritus obliquely stratified, including a mixture of down-washed shallow-water organisms with others that lived at greater depths; and third, the interior lagoon deposits, horizontally stratified and composed chiefly of inwashed organic detritus from the reef, of outwashed inorganic detritus from the island, in decreasing quantity upward, and of locally supplied organic deposits; but the lagoon deposits may also include corals in place, representing reef patches and pillars in the lagoon as well as belts of fringing reef along the inner margin.

The reef proper, composed, at least in part, of corals in place, is, as Darwin saw (118), a comparatively small fraction of the total

threefold structure of a large barrier reef. It is perhaps for this reason that corals in place are rather seldom seen in elevated reefs; certainly they should not be expected in the exterior talus slope of a recently uplifted reef. The steep-pitching beds of the exterior talus may rest on the less steeply inclined strata of volcanic detritus as in reefs A and C; or on the horizontal lagoon beds of a drowned reef as in reef B'; or exceptionally on an eroded volcanic slope as in reef B'', where the contact should be strongly unconformable.

The horizontal beds of the lagoon limestones must, on approaching the central island, overlie the earlier-formed fringing reefs of the spur ends and the detrital deltas of the embayments; and the fringing reefs and deltas must in all cases rest unconformably on the eroded slopes of their foundation. This is an important structural consequence of Darwin's theory which has been very generally overlooked; it is well supported by many facts. The inner margin of the lagoon deposits, including the fringing reefs and the deltas, must follow a sinuous line, because as subsidence progresses the dissected volcanic slope must necessarily, as Dana showed, but as Darwin did not understand, have an embayed shore.[1]

All of these features should be found in elevated reefs when they are dissected sufficiently to expose their structure. Among them all none is more important than the unconformity of the lagoon deposits on their eroded foundation, although mention has seldom been made of this significant structural feature in studies of coral reefs; for if the foundation is a slope of subaërial erosion—not a platform and cliff of marine abrasion—it must have stood above sea-level to suffer erosion before it was submerged to permit the formation of the unconformable and now elevated reef; and if the sloping surface of contact suffered a greater volume of erosion before the reef was formed upon it than could have taken place during the glacial epochs of lowered sea-level, or if it exceeds 240 feet in vertical measure, its submergence should not be ascribed wholly to the postglacial rise of the ocean, but at least in part to subsidence. A vertical measure of more than 600 feet is represented

[1] See Dana's "Confirmation of Darwin's Theory of Coral Reefs," *Amer. Jour. Sci.*, XXXV (1913), 173–88.

in the unconformable contact of an elevated and much dissected reef on its sloping volcanic foundation in the island of Vanua Mbalavu of the Fiji group;[1] hence subsidence there seems undoubtable.

Moreover, if three unconformable elevated reefs, B', B''', B'', stand in terraced arrangement, the sea-level being at S_2, it is by no means necessarily the case that they were formed during pauses in the elevation of their foundation, as has often been supposed; for their unconformity shows that a period of erosion followed by submergence must have taken place before emergence; hence the reefs may have been formed during pauses in submergence. If their structure is such as is shown in Fig. 1, B''' being superposed on the upper surface of B' and apposed on the front slope of B'', then the lowest reef must have been formed during an early pause in submergence, the highest reef at the climax of submergence, and the middle reef during a pause in emergence. If the changes of level thus indicated are of greater measure than 250 feet and are unlike on neighboring islands, they must be ascribed chiefly to local subsidence and upheaval and not to changes of the ocean surface around still-standing islands.

The structural relations of elevated reefs have seldom been observed in sufficient detail to determine the sequence of their formation; some unconformable terraced reefs that I examined on the island of Efate, New Hebrides, of which the highest was about 800 feet above sea-level, seemed to be superposed on one another, suggesting that they were formed during pauses in subsidence and afterward elevated.

It is not, however, only for elevated reefs that the test of unconformable contacts is of service. Many sea-level fringing reefs, occurring either at the inner border of barrier-reef lagoons, or alone fronting the ocean, have manifestly unconformable contacts with the eroded rocks of the coast that they border. This is repeatedly the case with the fringing reefs of volcanic islands, and it is even more clearly the case with the fringing reefs on coasts of deformed and eroded continental rocks, like those of New Caledonia, Queensland, and elsewhere. Wherever the volume of erosion

[1] "The Origin of Certain Fiji Atolls," *Proc. Nat. Acad. Sci.*, II (1916), 471–75.

below sea-level necessary to explain such contacts is greater than could have been accomplished during the glacial epochs of lowered sea-level, and wherever the depth of such erosion as indicated by the inclosing slopes of the drowned valley embayments is greater than 240 feet, or 40 fathoms, the submergence there involved cannot be explained by the postglacial rise of ocean-level, and local subsidence must be called on to account for the additional submergence, unless, indeed, the additional submergence is ascribed to a general rise of ocean-level due to recent uplifting of some other part of the sea bottom; but the combination of these two uniform changes of level would produce the same submergence on still-standing islands everywhere; whereas the sea-level and elevated reefs of the Pacific archipelagoes call for submergences varying in amount, date, and place, and alternating with emergences in varying order, thus producing a complication of changing levels that cannot be accounted for without local uplifts and subsidences such as Darwin's theory of coral reefs postulates. Thus at the outset of our inquiry the observed structures of sea-level and of elevated reefs appear to correspond very well with the hypothetical structures deduced from the theory of intermittent subsidence.

Prolonged crustal stability as postulated in the glacial-control theory.—In view of the citations from Darwin's book given above it seems fair to regard his theory of intermittent subsidence as adaptable to many different conditions, some of which are verified by the examples already adduced; not that every quoted opinion is correct, but that the careful consideration given to the different aspects of the fundamental postulate of subsidence shows that it was carefully examined, and that the theory which is based upon it is so elastic that it can accommodate a large variety of conditions and processes. Darwin's theory is in this respect strongly unlike the glacial-control theory, which is narrowly limited in its fundamental assumption of a "long period of nearly perfect stability for the general ocean floor," or, in other words, a "general crustal stability in the coral sea"; not that its processes require this narrow limitation for their operation, but that certain observed features, namely, the nearly level surface of submarine banks and

of atoll-lagoon floors occurring at similar depths are thought to demand the narrow limitation of general stability for their production.

It is true that the fullest exposition of the glacial-control theory contains certain statements which admit the exceptional occurrence of subsidence, such as: "The glacial-control theory fully recognizes that there has been Recent crustal warping in certain oceanic areas affected by coral reefs" (160[1]); and "perfect crustal stability in the intertropical zone during the Recent and Pleistocene periods is obviously not implied in the glacial-control theory" (222); but it also contains many statements of an opposite tenor which relegate subsidence to an insignificant position in the coral-reef problem. For example:

> Most of the reef platforms, like many banks situated outside the coral seas, have such forms, dimensions, and relations to the sea-level that they appear to have originated during a long period of nearly perfect stability for the general ocean floor. That is a conclusion forced upon the writer by close study of the marine charts. Its validity is a matter quite independent of the glacial-control theory. . . . . Submarine topography [of lagoons and banks] seems impossible of explanation without assuming crustal quiet beneath most of the deep sea during at least the later Tertiary and Quaternary periods [162].

Large preglacial volcanic islands are assumed to have stood still long enough to have been "peneplained and deeply decayed before the glacial period" (182). The preglacial degradation of such islands and their abrasion at normal sea-level, partly in preglacial time during temporary failures of reef protection, partly by the chilled and lower waters of the glacial ocean, demand

> much of the later Tertiary as well as the Pleistocene period, and thus during several million years the relation of sea bottom and sea surface was not significantly changed. However, such crustal stability is necessarily postulated only for the parts of the coral seas where *broad* platforms, about 75 m. below sea-level, are now found. For those areas the assumption of prolonged crustal stability, except for minute oscillations, seems absolutely unescapable. All theories of coral reefs must recognize it. . . . . The presence of a wide shelf or bench [lagoon floor?], a few tens of meters below sea-level, really represents a criterion for crustal stability during the later geological periods, generally including at least the time since the mid-Pliocene. The existence of the broad

[1] References to Daly's paper, "The Glacial-Control Theory of Coral Reefs," *Proc. Amer. Acad.*, LI (1915), 157–251, will be made by page number only.

plateaus [submarine banks, here assumed to be the product of abrasion during the glacial period], their accordant relation at present sea-level, and the impossibility of explaining them by any cause other than prolonged marine action [on still-standing preglacial islands of similar area], are the supreme facts emphasized in this paper. The weakest element in the subsidence theory is its failure to take account of them [221, 222].

Even in regions where Tertiary deformation is recognized, post-Tertiary subsidence is doubted, if not excluded. For example:

> New Caledonia and the Fiji Archipelago are generally regarded as located in a region of continental fragmentation. During the Tertiary period the eastern part of the Australasian continent was much faulted and otherwise deformed; the already dissected region sank beneath the sea and many valley bottoms became covered with water, scores or hundreds of meters in depth. . . . . Some bays of central islands [within barrier reefs] in the Western Pacific are explained [by Dana and others] by the sinking of those islands. However, the dating of that subsidence is not yet established and the actual bays may be due to the Pleistocene cleaning out of unconsolidated sediments which had been deposited in valleys, drowned during the Tertiary fragmentation of the Australasiatic continent. . . . . A similar explanation [of bays by subsidence] cannot be admitted for most of the coral archipelagoes. These lie outside of the Fiji–New Caledonia area [224, 226].

As to the implication in the last sentence that the embayments of reef-encircled volcanic islands in the Caroline and Society groups should not be explained by subsidence, I shall at this time only express my dissent from it. The object of the present paragraphs is to emphasize the contrast between the elasticity of the fundamental postulate of intermittent subsidence in Darwin's theory and the rigidity of the fundamental postulate of widespread and prolonged crustal stability in the glacial-control theory. Inquiry will be made later into the necessity of such contrast.

Possible subsidence of volcanic islands.—There is another aspect of the contrast between the two theories here under discussion that merits special consideration. This is the relation of many coral reefs to volcanic islands that rise from the deep ocean floor far from any continent; for it is generally agreed in all theories of coral reefs that even the foundations of atolls, where no volcanic rocks are visible, nevertheless consist of submarine volcanic cones and thus resemble the foundations of pelagic barrier and fringing reefs, where the volcanic cone is partly emerged. Darwin's theory of

coral reefs postulated an intermittent subsidence of the reef foundations; and, as the theory seemed true to its inventor, he based a second theory regarding the movement of the ocean floor upon the first, as will be further shown in the final section of this article. It is particularly to this oceanic corollary of the coral-reef theory that objection is made in the statement of the glacial-control theory on the ground of its supposed improbability. That theory therefore postulates "a long period of nearly perfect stability for the general ocean floor"; and the action of subsidence is made subordinate if not excluded. Yet it must be clear that any slow and intermittent process of local subsidence associated with volcanic cones will serve the needs of Darwin's theory just as well as a broad subsidence of the ocean floor; and in giving only a small value to such subsidence the glacial-control theory has, in my opinion, overlooked a very important factor of the problem.

It is true that there is a large body of older geological opinion that regards volcanic areas as areas of elevation and hence objects to a theory of coral reefs that postulates the subsidence of such areas. Thus Guppy asserted that the occurrence of barrier reefs and atolls in association with active volcanoes placed "the supporters of the theory of subsidence in a dilemma."[1] Hickson was persuaded that Passiac atoll, north of Celebes, could not have been built on a subsiding foundation, because an active volcano, Ruang, rises near by.[2] Murray had earlier made a more extreme statement; he thought that even extinct volcanoes occupy areas of elevation, and that, if areas of subsidence occur in the ocean floor, they must lie between the ranges of volcanic islands.[3]

There is, on the other hand, a considerable body of more modern and better-based opinion which associates volcanic activity, in some cases at least, with subsidence, as I shall elsewhere show in more detail, and as will here be pointed out for Hawaii in a later paragraph. It is immaterial to reef-building corals whether the

[1] H. B. Guppy, "A Criticism of the Theory of Subsidence as Affecting Coral Reefs," *Scot. Geogr. Mag.*, IV (1888), 121–37; see p. 136.

[2] S. J. Hickson, *A Naturalist in North Celebes* (London, 1889), p. 42.

[3] J. Murray, "On the Structure and Origin of Coral Reefs and Islands," *Proc. Roy. Soc. Edinb.*, X (1880), 505–18; see p. 516.

subsidence which gives them opportunity for upgrowth is locally associated with their volcanic foundation or is broadly manifested over large oceanic areas. In so far, however, as subsidence is associated with volcanic cones it is interesting to note that, as a result of the construction of many volcanic islands by long-continued eruptions through parts of Tertiary and later time, and as a further result of reef upgrowth upon such islands when they subside after their eruptive growth ceases, the ocean would be somewhat raised above the level that it had before the eruptions began; and thus the objection sometimes urged that the theory of subsidence is inconsistent with the prevalence of embayed continental coasts would be removed.

In support of the possibility of the local subsidence of volcanic reef foundations attention may be called to two recent articles. One is by Molengraaff,[1] in which the subsidence of an oceanic volcanic cone is causally connected with the elevation of its heavy lavas from a lower to a higher position, whereby the equilibrium of the ocean-floor crust is disturbed. It should be noted that oceanic volcanoes are more likely to cause isostatic subsidence than continental volcanoes, because the erupted materials of the latter are worn down and distributed far and wide in a relatively short geological period, while the materials of the former remain upon the site of their eruption indefinitely; indeed, instead of suffering loss by erosion, oceanic volcanoes enjoy a gain of volume by the addition of coral reefs if they stand in the warmer oceans, and it would therefore seem that the addition of a large volume of reef limestone to an oceanic cone would increase its tendency to subside.[2] The atoll stage of reef development may therefore be a late phase in a normal series of changes. It is not, however, intended to state that changes in the ocean bottom take place only in connection with volcanic islands; there is abundant evidence to the contrary.

The other article here to be cited in favor of the subsidence of volcanic islands is Daly's exposition of the glacial-

[1] G. A. F. Molengraaff, "Het Probleem der Koraaleilanden en de Isostasie," *Proc. k. Akad. Wet. Amsterdam*, XXV (1916), 215–31.

[2] "The Isostatic Subsidence of Volcanic Islands," *Proc. Nat. Acad. Sci.*, III (1917), 649–54.

control theory, above cited, in which the following views are expressed:

Nearly all of the oceanic islands and shoals seem to be of volcanic origin. Rising from a sea bottom 3,000 m. to 7,000 m. deep each volcano is very high in absolute measure and is also of notable area. The local extravasation of so much lava may well entail local, moderate sinking of the earth's crust. It is indeed possible that such sinking is very often caused directly by volcanic action on a large scale. . . . . Possibly, therefore, some of the drowned valleys and other physiographic features showing submergence of volcanic islands are to be explained by local sinking to the extent of a few meters or a few scores of meters [233].

This appears to me a very reasonable statement of the case, except in the limitation of the resulting subsidence to "a few scores of meters," that is, to only 1 or 2 per cent of the total altitude of a volcanic island that rises 2,000 meters over an ocean that is 6,000 meters deep. If the subsidence be causally associated with the change of attitude of the huge volume of lavas required to build a high volcanic island, a subsidence amounting to 10 or 20 per cent of the total height of the cone—that is, 1,000 or 2,000 meters—does not seem incredible. According to Molengraaff subsidence amounting to 100 per cent of the total altitude of a volcanic island, measured from sea bottom up, is to be expected. However this may be, the possibility that the volcanic foundation of a coral reef may locally subside must greatly weaken the chain of arguments which go to prove that "the submarine physiography [of certain atolls] spells crustal *stability* rather than unrest," and hence that subsidence cannot have played an important part in atoll formation.

Structural features of reefs formed according to the glacial-control theory.—The different classes of reefs, fringing, barrier, and atoll, are derived from each other, according to the theory of intermittent subsidence, as illustrated in Fig. 1 (p. 205); they are formed independently according to the glacial-control theory; and, as atolls are the most abundant and therefore receive chief consideration in Daly's discussion, their structural features will be first examined here. They are in essence as follows: A preglacial volcanic island, *UV*, Fig. 2 (drawn on a larger scale than Fig. 1), is reduced, partly by subaërial erosion, partly by abrasion, during a long period of quiescence to an island of low relief, *U'W*, while a bank, *UB'*, is

formed around it of detrital deposits, T', in which coral reefs may be included. The ocean is then lowered about 40 fathoms from S_1 to S_2 during the glacial epochs of the glacial period, and the deeply weathered island is reduced by abrasion to a platform, $B''XZ$. The exposition of the glacial-control theory does not attempt to analyze the effects of alternating glacial and interglacial epochs, but assumes an almost continual action of abrasion, as is implied in the statement, "The sea was actively attacking the islands and continental coasts throughout nearly the *whole* glacial period" (180). Such continuity of abrasion seems doubtful, in view of the greater length and probably higher temperature of the last interglacial epoch than of postglacial time; it is also questionable whether

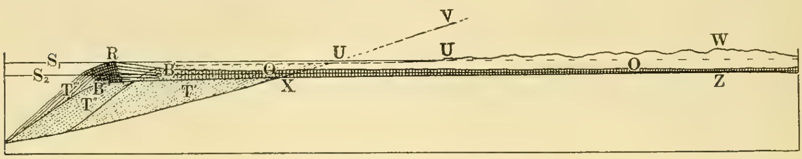


FIG. 2.—Structure of an atoll

abrasion would be accomplished at the same level during successive epochs of glaciation; but I shall not pursue these details as the main question is sufficiently complicated without them.

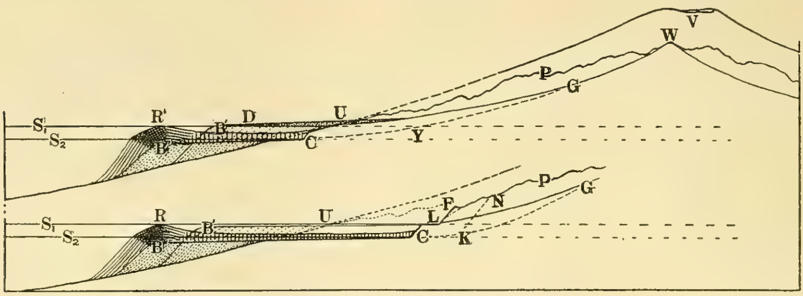
Let it be provisionally agreed, therefore, that abrasion was essentially continuous at one level; then the completely abraded platform must gain the form of a flat cone, the exterior part of which consists of a new ring of detritus, T''. If a central remnant of a large island remains unconsumed, it should be rimmed with cliffs; but the residual granitic island of Mahé in the center of the vast Seychelles bank in the southern Indian Ocean is not cliff rimmed. If a preglacial island, 50 miles in diameter, be completely abraded, the platform may well be 20 fathoms deeper at its margin, B'', than at its center, Z. When the ocean warms and rises in postglacial time and a reef, R, grows up on the platform margin, the exterior detrital slope, T''', is slightly extended, and the lagoon is aggraded sufficiently (vertical lines) by the addition of horizontally stratified detritus, deposited unconformably upon the truncated volcanic rocks, to change the platform from a flat cone to a shallow saucer, ROO; or if, for any reason, the reef is not built up, the

platform remains as a more or less aggraded and nearly level submarine bank.

The structures thus inferred are definite enough to establish the theory that accounts for them, if their existence be assured; but as only the form and the surface constituents of atolls and submarine banks are known, the theory which involves the undemonstrated existence of abraded platforms remains uncertain. The boring at Funafuti, the depth of which was about five times the difference of level assumed between S_1 and S_2, Fig. 2, should have penetrated the detrital deposits, $T''T'$, below the reef proper, if that atoll were formed in the manner here stated; it might have penetrated volcanic rocks also, as the section is here drawn, but no such rocks were reached. According to the theory of subsidence the boring might have penetrated true reef structure, or a combination of reef, lagoon, and talus structures, for its entire depth, as above noted. Some of the experts who have examined the rock core think that the boring was altogether in true reef-rock of shallow-water formation, some are noncommittal, some think it was mostly in talus deposits. Discrimination is doubtless difficult; but the evidence given by the absence of deep-water organisms from the boring is significant. A boring of similar depth in the lagoon center would have penetrated an abraded platform of volcanic rocks, if such a platform exists there; but several borings, all encountering volcanic rocks at the same moderate depth of about 40 fathoms, would be necessary to demonstrate that the rock surface had the form of a platform.

The uniform postglacial rise of the ocean suggests that all existing reefs should be of similar volume above their abraded foundation; a later section is devoted to this point. The belief that the flatness of the floors of atoll lagoons and of submarine banks and the similarity of their depths can be explained only by their having almost flat platforms of uniform depth as foundations will also be examined later in some detail. Evidently, if atolls that had been formed according to the glacial-control theory were sufficiently elevated and dissected, the flat platform would be revealed if it existed; also this possibility is briefly considered in a later paragraph.

The glacial-control theory was framed chiefly to account for atolls; barrier reefs receive less attention, but their formation appears to be conceived as follows: Let a volcano, *VU*, Fig. 3*a* or 4, of less ancient origin than those which were reduced to low relief in preglacial time, be submaturely or maturely dissected at the beginning of the glacial period, so that its spurs, *WPU*, are separated by radial valleys, *WGU*, while an alluvial delta-belt, *UD*, lying on a bank of wave-washed detritus, *B′*, with more or less coral in it, surrounds the non-embayed shores. Fig. 3*a* represents conditions which will result in producing a narrow-lagoon barrier reef in postglacial time; Fig. 4 those which will result in producing a wide-lagoon barrier reef. [According to my own view this statement



FIGS. 3*a* (above) and 3*b* (below).—Structure of a barrier reef, showing conditions which will result in producing a narrow-lagoon barrier reef in postglacial time.

should be modified by excluding preglacial reef growth around the stationary island, for reasons stated in connection with the structural features of reefs formed during subsidence, and by adding a less or greater amount of preglacial abrasion, producing a rock platform, *UL*, Fig. 3*b*, back of which the island spurs would be truncated in cliffs, *LF*, and outside of which a detrital bank, *UB′*, would be accumulated.]

As a result of the lowering and cooling of the glacial ocean, the valleys, *WGU*, are deepened to *GC*, Fig. 3*a* or 4, and widened as much as the duration of lowered sea-level allows; at the same time a marginal platform, *B′′C*, is cut down and built out about 40 fathoms below normal sea-level; but the retrogressive abrasion of the platform is supposed to go only so far as to cut small cliffs, *C*, in the resistant lavas of the volcanic island. Later, as a result of the

rising and warming of the postglacial ocean, a reef, *R*, is built up on the platform margin, inclosing a lagoon, the inner shore line of which will [if no preglacial cliffs were cut, and if the low cliff, *C*, abraded during the glacial period, is submerged] be characterized by tapering spur-end points, *PU*, between embayed valley mouths, *UY*. The present depth of the lagoon, decreased by postglacial aggradation (vertical lines), must be less than the rock-bottom depth of 40 fathoms.

In assuming that the spur ends will not be clift, this outline seems to me erroneous for two reasons: first, because the time required to reduce large preglacial islands to the broad platforms that are assumed to underlie the floors of large atolls and submarine

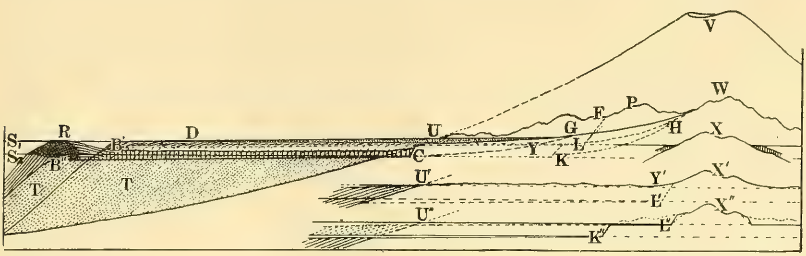


FIG. 4.—Structure of a barrier reef, showing conditions which will result in producing a wide-lagoon barrier reef in postglacial time.

banks, as in Fig. 2, ought to suffice for the cutting of strong spur-end cliffs, like *KN*, Fig. 3*b*, around the shores of younger and higher islands, particularly around such islands as today have narrow-lagoon barrier reefs, or only fringing reefs, like Rarotonga; secondly, because the time required to widen the deepened valleys, *GC*, by the slow process of weathering the resistant lavas on their sides so that they shall form embayments with the observed width of half a mile or more when the ocean resumes its normal level, ought surely to suffice for the cutting of strong spur-end cliffs. Whether these cliffs, *KN*, should be cut back of the inferred preglacial cliff, *LF*, is an uncertain matter; if so, the spurs today should terminate in steep and well-defined cliff faces, but this is rarely the case, as will be further shown in a later section; if not, a shallow rock platform, *L*, should front the weathered and battered preglacial cliffs, *LF*; but platforms so situated are unknown.

This aspect of the problem deserves special consideration in connection with "almost-atolls," or large reef-inclosed lagoons having one or more small and steep-sided, yet not clift, volcanic islands near their center, X, Fig. 4, as in the great reefs of Truk (Hogoleu), in the Caroline Islands, and of the Gambier Islands, southeast of the Paumotus, previously mentioned. A careful examination of the problem shows that it is difficult, if not impossible, to develop steep slopes on a small, non-clift central island without the aid of subsidence. The residual knob, X', of a large, still-standing volcano would be surrounded in preglacial time by a broad lowland, $U'Y'$, or by a shallow wave-cut platform, $L''U''$, worn on volcanic rocks, outside of which would lie a broad exterior bank. If surrounded by a lowland, the lower slope, Y', of the residual knob, X', would today be of gentle declivity, unless its borders were clift by abrasion during the glacial period; but as small central islands do not possess spur-end cliffs, L', with submerged bases, this possibility is excluded. If such islands were formerly surrounded by a preglacial wave-cut platform, $L''U''$, some part of the platform should today remain as a shoal in the inner part of the lagoon inside of the cliff, K'', cut by the lowered ocean—particularly within the polygon marked by the several residual islands of Truk—for it is not to be supposed that abrasion by the lowered glacial ocean should just suffice to cut away all the preglacial platform; but residual platforms of this kind are unknown. None of these difficulties arises under the theory of intermittent subsidence.

Hence the actual features associated with barrier reefs cannot be matched by the features deduced from the theory of glacial control unless neither preglacial nor glacial cliffing of the spur ends on non-subsiding islands takes place to any great extent. This seems to me highly improbable; hence I am led to conclude that as a rule high volcanic islands, even if clift in their earlier history, had already subsided sufficiently in preglacial time to drown their cliffs and to allow the formation of barrier reefs before the ocean was chilled and lowered; and that, except along the margin of the coral zone, the flanks of the reefs, which emerged while the ocean was lowered and chilled, were occupied by living organisms of some kind so that the islands were continuously protected from wave attack. This

aspect of the problem has been dealt with more fully in some of my earlier papers and is further treated in later sections of this article.

Barrier reefs and their lagoon deposits, if formed under the conditions and processes of the glacial-control theory, should, when sufficiently elevated and dissected, be found to lie unconformably with small thickness, not on a slope of subaërial erosion, but on an abraded platform, the outer part of which truncates a series of inclined detrital deposits, while the inner part truncates a series of volcanic rocks and is limited by an ancient sea cliff, more or less weathered. But it should be noted that if such a reef were elevated long enough ago to have been well dissected, its formation could not have been of postglacial date; it must have been either preglacial or interglacial; if interglacial, then the continuity of abrasion through the glacial period is disproved; if preglacial, the reef should not rest on an abraded platform, but should constitute (on the supposition that no subsidence took place during its formation) a conformable member of the exterior detrital deposits, the lowest member of which should lie conformably upon a non-eroded volcanic slope.

The elevated and greatly dissected reefs of Vanua Mbalavu, in eastern Fiji, the best examples of their kind that I have seen, do not fulfil any of these conditions; their limestones lie on slopes of subaërial erosion, the vertical measure of which is, as already noted, much greater than the greatest possible change of ocean-level during the glacial period; whatever the date of formation of these reefs, the occurrence of subsidence before or during their formation seems to me demonstrated.[1] A single example of this kind cannot, however, have great general value; further exploration and investigation of other elevated reefs must be made with the considerations above outlined in mind before this phase of the problem can be far advanced. Abundant opportunity for such investigation is offered by the Philippines, Pelew, New Hebrides, Solomon, and other island groups, where the unconformable contact of elevated reefs with their eroded foundations is implied by the incomplete records now available.

[1] "The Origin of Certain Fiji Atolls," *Proc. Nat. Acad. Sci.*, II (1916), 471–75.

[*To be continued*]

SANTO DOMINGAN PALEONTOLOGICAL EXPLORATIONS

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In the early seventies, forty-four years ago, Professor William Gabb published the results of his topographical and paleontological explorations in Santo Domingo.[1]

Since that time no paleontological researches have been made on the island until the writer's expedition up the Yaqui Valley in 1916. Fully illustrated and detailed accounts of the latter have been published in *Bulletins of American Paleontology;*[2] but a comparative and historical sketch of the subject and a statement of the present status of our knowledge may perhaps be deemed of interest.

Before the time of Gabb, in 1849 and 1850, paleontological collections had been made by Colonel Heneken, of the British army. This gentleman, who was the pioneer, was stationed for a time at the fort at Monte Cristi, and his interest was awakened by finding the exquisitely preserved fossil shells at various places up the valley of the Rio Yaqui and its southern tributaries. In the interval between revolutions and military duties he obtained two collections of fossils which he sent with explanatory notes to the Geological Society of London. For many years the fossils were kept in the rooms of that Society; but lately they have been handed over to the natural-history division of the British Museum.

The shells Heneken collected were described by Sowerby, and interesting deductions on their relationships and affinities were written by Moore. Both Moore and Sowerby were quick to see their resemblance to the fossils of Dax in the Bordelais region of

[1] William Gabb, *Trans. Amer. Phil. Soc.*, XV (1873).

[2] "Santo Domingo Type Sections and Fossils," *Bull. Amer. Pal.*, V, No. 29 (March-April, 1917), 251 pp., 39 pls.; No. 30 (May, 1917), 45 pp., 3 pls.

France, and pronounced them of Miocene age.[1] They raised the question, of late years also set forth by Dall, whether more than one formation was represented. They called attention to the resemblance of certain of the fossils to the recent deep-sea and Pacific forms. Indeed, the brief article of Moore shows a highly philosophic interpretation of the data. Later, in 1872, Dr. Guppy of Trinidad, on a trip to London, reopened the Heneken collection, made a number of excellent illustrations, and described some of the specimens which further study had showed to be new.[2]

Gabb agreed with these pioneers in assigning a Miocene age to the fossils from the Yaqui Valley, but emphatically denied the possibility that more than one formation was represented, coinciding in this with Heneken. Gabb regarded the entire valley as made up of fossiliferous beds of late Miocene time. The belief that this constituted a stratigraphic unit led him to disregard entirely localities and zones in collecting, and his otherwise fine collections are very seriously marred by having been labeled solely: "Miocene, Santo Domingo."

Our 1916 expedition was undertaken with the express object of determining the exact stratigraphic sequence. The party consisted of the writer, Mr. Karl Paterson Schmidt, and Mr. Axel Olsson. Despite the dangers of the revolution led by Desiderio Arias, we succeeded in collecting over four hundred species of molluscs, many corals, bryozoa, foraminifera, echinoderms, and crustacea. The molluscs are at present in the museum of Cornell University, while all the other groups were presented to the United States National Museum in recognition of the very kind assistance given by Dr. Vaughan and his associates in identifying them for us. About a third of the molluscs were new species, and, as practically none of Gabb's species had been figured, every effort was made to illustrate all the species as beautifully and accurately as possible, more than five hundred and eight figures being given in the writer's report in the *Bulletins of Paleontology*.

As a result of these faunal studies and of the very careful sections obtained along the various rivers where the fossiliferous

[1] See *Quart. Jour. Geol. Soc.*, London, 1850, 1853.

[2] *Ibid.*, 1872.

beds were found, I believe that three formations[1] are represented, named from their characteristic fossils and given in ascending order: the *Orthaulax inornatus*, the *Aphera islacolonis*, and the *Sconsia laevigata* formations. The *Orthaulax* horizon is approximately equivalent to the Rupelian of Europe, ties up with the Tampa silex beds of Florida, and is Oligocene. The *Aphera* horizon is the Upper Aquitanian of Europe, which is Lower Miocene, and is linked with the marls of the Chipola River, Florida. The *Sconsia* horizon is the Burdigalian of Europe, which is Middle Miocene and is synchronous with the Oak Grove sands and the cross-bedded Alum Bluff beds[2] of Florida.

In closing the Oligocene with the Rupelian we agree with the European geologists. In this country custom varies, certain very prominent geologists continuing the Oligocene farther up because of the absence of any conclusive stratigraphic break. According to the latter view no Miocene is present in the Antilles, because it is thought that they were so highly elevated during that period that the materials deposited lie now out at sea.

There seems, however, to the writer no necessity for postulating this great change of level, and the supposition that Oligocene time in the Antilles passed on into Miocene with continuous sedimentation appears more probable.

In connection with this question of Miocene versus Oligocene age, the discovery by Dr. Sellards, director of the Florida Survey, of Miocene vertebrates in Florida is illuminating. Our conclusions of the Miocene age of the *Aphera* formation in Santo Domingo and through it of the Alum Bluff cross-bedded sands and the sands of Oak Grove were made independently of Dr. Sellards' results, with which they harmonize.

Looking back to early Miocene times we may picture to ourselves an arm of the sea running east and west in the northern part of Santo Domingo and occupying what is now the valley of the Rio Yaqui. In the shallow waters was a rich molluscan fauna, solitary and compound corals were common, crabs of various genera and hermit crabs lurked about, bryozoa incrusted the

[1] See Correlation Table, *Bull. Amer. Pal.*, No. 30, 1917.

[2] See the writer's drawn section, *Bull Amer. Pal.*, No. 15 (1902), p. 57.

rockweeds. A marked feature was the local distribution, certain assemblages being limited to certain coves. Univalves far outnumbered bivalves. The genera *Terebra*, *Conus*, *Drillia*, *Cythara*, *Cancellaria*, *Oliva*, *Marginella*, *Mitra*, *Strombina*, *Murex*, *Cypraea*, *Strombus*, *Cerithium*, *Pyramidella*, and *Turbonilla* abounded. Among the bivalves was a profusion of Arcas, while the genera *Chama*, *Pecten*, *Cardium*, *Protocardia*, *Chione*, *Petricola*, *Tellina*, and *Corbula* were represented by many beautiful forms. Lignitic beds, gravels, and clays were being deposited. As the Middle Miocene was ushered in the change of conditions began first to be felt by the sensitive corals, then the sluggish molluscs were affected and a large proportion of them ceased to exist and were replaced by different forms. Members of the Myrtle, Laurel, and Mimosa families grew upon the neighboring shores, with a number of woods of new species not known from elsewhere.

The Pacific element in the fauna of the Yaqui Valley is very marked in some cases. This fact that the nearest living allies and apparent descendants of certain of the fossil species are now on the west coast or in the Gulf of California might seem to indicate an Oligocene age of the deposits. But if we regard sedimentation as proceeding uninterruptedly, there is no reason why the species may not have lived on in the Antilles for some time and not suffered immediate extinction. Moreover, Dr. Vaughan has been led to suggest from the evidence gathered from fossil corals of the Californian region that a trans-Isthmian passage may have existed later than Oligocene time. This appears strengthened by Professor Harris' observations of the Pacific and Gulf of Californian affinities of the Miocene molluscan fauna of the Galveston deep well. Our Antillean Miocene is, however, entirely distinct from the deep-well Miocene faunas of Texas and Louisiana, nor has it any resemblance to the cold-water Chesapeake Miocene of Maryland and Virginia.

Certain of the fossils of the Yaqui Valley most closely resemble species now living in the deep sea. Undoubtedly, however, the fossils were shallow water in habit of life because their associates all conclusively prove this; even the foraminifera being all genera now characteristic of shallow waters. Thus indications are

furnished of a considerable number of migrations since Mid-Tertiary time from the shallows to the depths, and an illustration is given of one mode of derivation of the abyssal faunas.

The vanished land of "Antillia" delights the imagination. It has taken form under the bold and able pen of Bailey Willis, who represents it as at one time joined to Yucatan and at another to Florida. Investigations of the fossil invertebrates and comparisons of the land molluscs of Central America with those of Santo Domingo may give more probability to this ancient land. At present we only know definitely that the fossil fauna of the Yaqui Valley of Santo Domingo is most closely allied to that of Bowden, Jamaica, and also has affinities with the island faunas of Cumaná, Trinidad, and Martinique and with the Isthmian fauna of Gatun.

BLOCK FAULTING IN THE KLAMATH LAKES REGION

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In the summer of 1915 the writer gathered some physiographic data of more than ordinary interest concerning block mountains in the Klamath Lakes region of Oregon; but because the data were based on hasty observations, he hesitated to publish them without further verification. The following winter, learning that Dr. G. K. Gilbert planned to visit parts of the Great Basin, I placed my notes at his disposal in the hope that he might verify the essential accuracy of some of my more hasty deductions. This he has done, and I make bold to place my observations on record. In doing so I apologize for the incompleteness of the data, but trust that the importance of the features observed will compensate in some measure for the paucity of description. I desire to express my appreciation of Dr. Gilbert's courtesy in permitting me to quote his confirmation of my general conclusions, and at the same time to acquit him of any responsibility for possible errors in the following statements. The region discussed is shown on the Ashland and Klamath topographic quadrangles of Oregon.

On emerging from the narrower portion of Anna Creek valley and entering the broadly open northern end of the Klamath Lakes basin, the observer is at once impressed with the topographic indications of block faulting. On the west is the east-facing scarp of the Cascade Mountains, not very imposing it is true, but remarkably straight and rising abruptly from the basin floor, strongly suggesting a fault scarp in the face of which a number of short streams have cut their valleys. The Crater Lake cone is seen to rest upon the northward continuation of the supposed fault fissure, while farther south another volcano, unnamed on the map, occupies a similar position. Such a distribution of volcanoes is rather suggestive in connection with the fault theory, and the

apparent continuation of the cone slopes unbroken into the basin indicates that in considerable part at least the eruptions followed the faulting. A mud flow from the Crater Lake volcano came recently enough to descend the already formed Anna Creek valley, and even to spread out over the floor of the basin for some distance if one may judge from topography alone. No sections were observed out in the basin, but farther up the valley Anna Creek

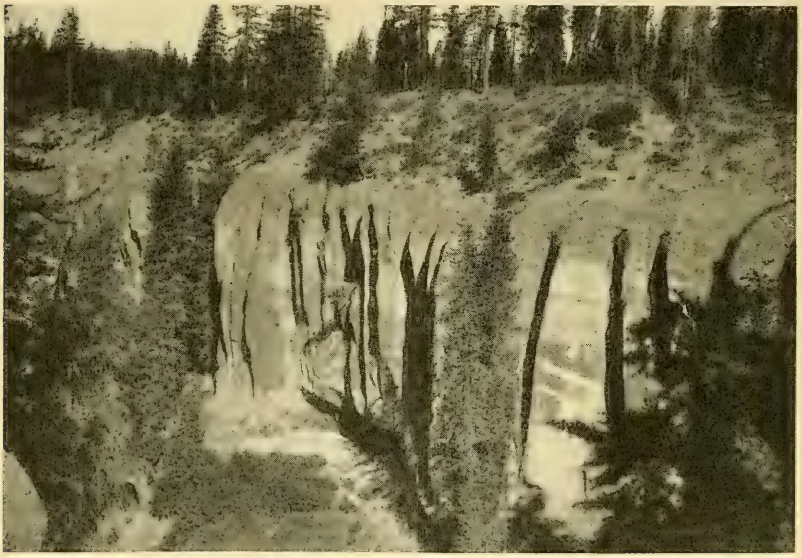

FIG. 1.—Joint structure in volcanic ash, Anna Creek valley. (Photo by D. W. Johnson.)

has trenched the flow, revealing a beautifully jointed ash deposit (Fig. 1). A sufficient number of lateral tributaries greatly to dissect the deposit has not yet been developed; partly, no doubt, because of the porosity of the ash.

On the east side of the Klamath basin is a lower scarp remarkable for its straightness and for the small extent to which it has suffered from the agents of erosion. It is far more youthful in appearance than the higher Cascade scarp. Because of its steepness the low, west-facing scarp is in striking contrast with the very gentle slope which declines eastward from its crest, and of

which one may catch an occasional glimpse from the automobile road. The topographic relations clearly indicate a very young block mountain with steep fault face on the west and gentle back-slope on the east. For convenience we may call this the "Fort Klamath block" from the little settlement of that name near the base of the west-facing scarp. The northern portion, at least, of the Klamath Lakes basin, bounded as it is by higher fault blocks on both the east and the west, would therefore appear to represent a graben, if this term may properly be applied to a relatively depressed block between two faults of different date. We will in any case refer to it simply as the "Klamath graben."

Toward the north the fault scarp of the Fort Klamath block appears to swing westward to intersect the Cascade scarp under the mass of the Crater Lake volcano. Indeed it would seem that the intersection of the two supposed fault fissures most probably lies beneath the surface of Crater Lake itself. Toward the south the Fort Klamath block dies out, to be replaced by the Modoc Point block described below.

One feature associated with the young Fort Klamath block deserves special attention. It is well understood that if a block mountain is raised across the path of a transverse stream so slowly that the stream is able to cut down its channel as fast as uplift occurs, the stream will maintain its antecedent course through the mountain. The transverse gorge of the Sevier River through the Cañon Range in Utah appears to be of this origin. On the other hand, if successive slight uplifts occur in too rapid succession, or if a single uplift is sufficiently great in amount, the river may be defeated in its purpose and turned aside. Somewhere, according to theory, we might reasonably expect to find one or more examples in which the river maintained its antecedent course for a long time, say until the block was raised halfway to its present altitude, but was then turned aside by a period of too-rapid uplift.

The Fort Klamath region seems to present just such a case. South of Fort Klamath settlement one sees from the automobile road what at first appears to be a hanging valley opening in the face of the fault scarp about halfway between crest and base

(Fig. 2). From a distant view one gets the impression, however, that the elevated valley floor slopes eastward, or away from the fault scarp instead of toward it. I interpreted this to mean that a stream formerly flowed from west to east through the block, probably to unite with Williamson River, and that it maintained its antecedent course until half the present altitude of the rising block had been attained; then an excessive uplift dammed the stream and turned it southward along the Klamath graben, while the deserted valley was later raised to its present altitude by continued uplift of the range. Regarding this remarkable valley Dr. Gilbert writes: "The hanging valley you noted seems to be the only one of its type. I was able to verify your interpretation."

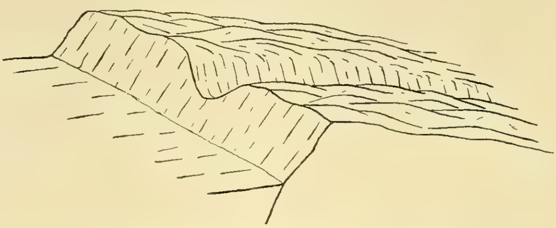

FIG. 2.—Deserted antecedent gorge in uplifted lava block south of Fort Klamath settlement.

In this connection I may perhaps refer to another possible example of the same physiographic type, recorded more than ten years ago, but not described in print because of the hasty character of the observations on which my tentative interpretation was based. In the summer of 1906 I passed through the Parowan Valley at the western base of the high plateaus of Utah. This depression (Fig. 3) is well shown on the Kanab topographic quadrangle, and was interpreted as a graben similar to the one described above. The great fault which bounds the valley on the southeast is abundantly attested by both physiographic and stratigraphic evidence, as I proved by several traverses across the fault southeast of Summit, Parowan, Paragoonah, and elsewhere. On the northwest the valley floor terminates abruptly at the base of a pronounced scarp, which is more or less dissected, but which shows occasional well-marked triangular facets such as characterize the fault faces

of certain block mountains. The topography strongly suggests that Parowan Valley is a down-dropped block, bounded on the southeast by a fault-block plateau and on the northwest by a fault-block mountain whose more gentle back slope is toward the northwest.

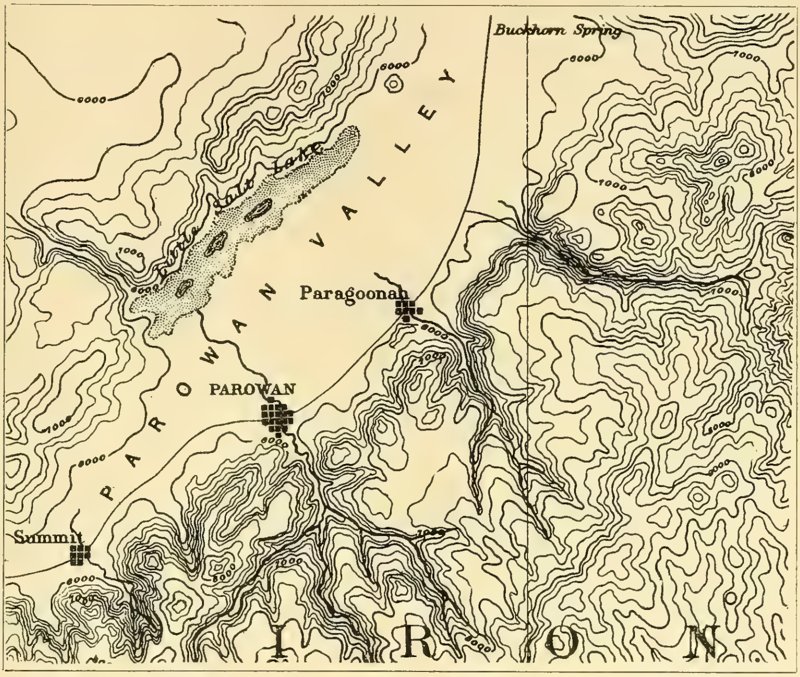

FIG. 3.—The Parowan graben, Utah, showing abandoned antecedent gorge through block mountain on the northwest.

Cutting transversely through the block mountain just mentioned is a remarkable gorge directly in line with the extended lower course of a stream which rises in the block plateau and flows northwest through the town of Parowan. According to the map, however, the stream does not continue through the gorge at the present time, but terminates in a salt lake at the base of the fault scarp. The topographic relations suggested the possibility that a recent upfaulting of the block mountain had obstructed the Parowan stream and left the antecedent gorge deserted. If this be the

correct interpretation the case is of interest as representing an earlier stage of the history recorded in the Fort Klamath example; for in the Parowan case the deserted valley has not yet been raised much above its former level, and the lake initiated by the rising obstruction has found no new outlet. It is possible that heavy rains might so raise the lake-level as to cause it to spill out through

FIG. 4.—Fault-block "splinter" on face of young block mountain. Modoc Point looking north from Plum Ridge. (Photo by A. K. Lobeck.)

the gorge itself before another outlet was found. Unfortunately I was not able to visit the entrance to the gorge, nor otherwise to test the validity of my tentative interpretation. Observations based on a reconnaissance map with contour interval of 250 feet, supplemented by visual inspection from a distance of four or five miles, must not be accorded too high a value.

Returning to the Klamath graben we may note that from Cihloquin southward a very young fault scarp forms the imposing

east wall of the graben. This is the western face of what may be called the Modoc Point block mountain, which stands in the same relation to the graben as the Fort Klamath block farther north, and, like the latter, has a more gentle eastern back slope. The west-facing fault scarp is remarkable for its youthful appearance, erosion having modified it but slightly, and for the straightness of its base line for many miles at a stretch. At Modoc Point itself the strike of the fault changes rather abruptly from N.–S. to S. 35 E.

FIG. 5.—Slickenside surface exposed along road cut in north end of Plum Ridge. (Photo by J. P. Buwalda.)

On the face of the range farther south is a prominent "fault-block splinter," clearly shown in Fig. 4, from a photograph of Modoc Point looking northward from the northern end of Plum Ridge. The same view illustrates the youthful character of the fault scarps.

It must not be supposed that the back slopes of the Fort Klamath and Modoc Point blocks are as smooth and featureless as their fault faces. Both blocks are remarkably youthful in the present cycle of erosion, as the descriptions of their fault scarps fully indicate; but no description would be complete which did not include an account of the stage of erosion reached in the pre-faulting cycle, as indicated by the topographic aspect of the back slopes. Our route of travel gave little opportunity for observation

on this point; but it may be said that both the contours of the Klamath topographic quadrangle and such glimpses as we secured of the back slopes agree in suggesting that the prefault topography was moderately rugged. The back slope of neither block appears to be as featureless as it would be had the region subjected to faulting consisted of a young lava plain on the one hand, or, on the other hand, of a volcanic region reduced by long-continued erosion to a peneplain. Dr. Gilbert writes that the reconstruction of the prefaulting relief would be a difficult task, because the great blocks have been "intricately sliced and dislocated on a small scale; and one of the marvelous features of the region is the association of major faulting with elaborate contemporaneous minor faulting."

West of the southern end of the Modoc Point block is a subsidiary fault block called Plum Hills or Plum Ridge. Near the northern end of the steep, undissected scarp which bounds this ridge on the west there is a magnificent exhibition of slickenside surfaces visible from the passing train. Here we have preserved that rare phenomenon, a portion of the actual fault plane of a fault-block mountain. The perfection of the slickenside surfaces may be inferred from the fact that one of them has been used as a "bill board" upon which are painted the advertisements of certain business houses, as shown in Fig. 5.

THE NORTHWARD EXTENSION OF THE PHYSIOGRAPHIC DIVISIONS OF THE UNITED STATES

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PART II

THE GREAT PLAINS PROVINCE

East of the Rocky Mountain System lies a plateau area that slopes gently away from the mountains. Custom has firmly attached to the part of this region lying within the United States the name of "Great Plains." In the present paper this name will be used to include the Canadian and Alaskan sections of the province.

The Great Plains extend uninterruptedly from the Pecos and Rio Grande rivers northward through the United States[1] and Canada to the shores of Great Bear Lake.[2] At this place the Mesozoic and Tertiary rocks of the Great Plains Plateau are cut off by a westward extension of the pre-Cambrian rocks of the great Laurentian Plateau and the province becomes restricted to a narrow belt. However, it widens again near the boundary between the Northwest Territories and Alaska, and gradually develops into the Anatuvuk Plateau of Alaska which has a width of about 150 miles. This section of the province terminates near the one hundred and sixty-third meridian, where its mountainous southern boundary closes with the Arctic shore line.[3] As shown on the accompanying map the northern part of the province bends to the west in conformity with the general trend of the neighboring Cordillera.

The western boundary of the province throughout its entire extent is the Rocky Mountain System. These two divisions are sharply distinguished topographically. On the east the province

[1] N. M. Fenneman, *Ann. Assoc. Am. Geog.*, IV, pl. 1.

[2] C. A. Young, *Geol. Survey Canada, Pub. 1085*, p. 107.

[3] A. H. Brooks, *U.S. Geol. Survey, Prof. Paper 45*, pp. 46, 47.

is generally satisfactorily delimited. It is separated from the Central Lowland for considerable distances by an eastward facing escarpment from 200 to 1,000 feet high. The most conspicuous

portion of this escarpment (the Missouri coteau) begins near the southern boundary of North Dakota and extends northward to about the fifty-fourth parallel.[1] Beyond this to the vicinity of

[1] C. A. Young, *loc. cit.*

Great Bear Lake the boundary is essentially the contact of Mesozoic and younger sediments on the west with old pre-Cambrian rocks on the east. In the Anatuvuk Plateau section, the contact of Mesozoic and Tertiary rocks on the south with later Tertiary sediments of the Arctic Coastal Plain on the north may be regarded as the boundary line. This line is not easy to recognize everywhere in the field. In many places the merging of plain and plateau is imperceptible; in other places the coastal plain is wanting and the waves of the Arctic Ocean dash against the base of the plateau scarp.[1]

Many of the features of the Great Plains in the northern part of the United States owe their origin and character either to base-leveling or glacial accumulation, or to both. In brief, the topography may be described as a broad expanse of moderately rolling plateau broken here and there by valleys and irregularly dissected tracts, and rising westward to the foot of the Rocky Mountains at a rate of four or five feet to the mile. Standing above the general surface are a few residuals that resisted the Tertiary base-leveling. Turtle Mountain near the boundary of North Dakota and Manitoba is typical of these. Glacial moraines with their accompanying bowlder ridges, lakes, and ponds are characteristic.

Approximately the same conditions are continued northward into Canada to about the fifty-fourth parallel. The topography of this section is also irregular and rolling. The plateau surface rises from 2,000 or 2,500 feet at the eastern escarpment to about 4,000 feet, where it meets the mountains on the west. Residual masses, such as the Cypress Hills and Wood Mountain, represent the resistant and unreduced portions of a once higher plain.[2] The numerous ponds and lakes scattered over the surface are glacial features.

The Anatuvuk Plateau of Alaska is also a dissected peneplain (Eocene or Miocene) which has been elevated to an altitude of about 2,500 feet at the northern base of the Endicott Mountains, from which elevation it descends gradually to about 800 feet, where it merges with, or overlooks, the Arctic Coastal Plain.[3]

[1] A. H. Brooks, *loc. cit.*

[2] C. A. Young, *op. cit.*, p. 107.

[3] A. H. Brooks, *op. cit.*, pp. 279, 280.

Structurally the Great Plains are a unit from Texas to Alaska. Although the strata of the divisions within the United States lie sensibly flat for short distances, the structure of the bedrock (Paleozoic or Mesozoic sediments) has the general character of a great geosyncline which rises sharply on approach to the Rocky Mountains, where the steeply inclined eastward dipping strata appear in the form of "hogback" ridges fringing the Front Ranges of the Rocky Mountains. A *regional* westward dip of the plains strata is general for the province, but it is modified locally by structural deformations of some importance. The eastern outcrop of the westward dipping strata is marked by the escarpment and coteaus previously referred to.

Similar structural features exist in Canada[1] and on the whole in Alaska, though on the Anatuvuk Plateau the Mesozoic strata appear to have been thrown into a series of broad, open folds, and even the early Tertiary deposits have been subjected to minor deformation.[2]

In early Tertiary time the Great Plains of the United States were raised out of the sea and have remained a land surface ever since. The Tertiary period was one of active erosion, and during that time the region was base-leveled, excepting the residuals previously cited. The western part of the province had the greater initial uplift, consequently it was susceptible to greater erosion. All strata were beveled regardless of changing dip and hardness. Another great uplift in late Tertiary time began the present erosion cycle. In both the United States and Canada this later erosion has caused deep dissection in the western parts of the Great Plains and has almost base-leveled again the low plains to the east.

In Alaska the base-leveling of the Anatuvuk Plateau is assigned to the late Eocene or the Miocene epoch,[3] and the unconsolidated deposits which overlie the eroded strata are supposed to be of Pliocene age. If this time is correct these deposits correlate closely in age with the terrestrial deposits that are so widely scattered over the Great Plains of the United States.

[1] C. A. Young, *op. cit.*, pp. 108–13.

[2] A. H. Brooks, *op. cit.*, pp. 278–80.

[3] A. H. Brooks, *ibid.*

THE WESTERN LAKE SECTION OF THE CENTRAL LOWLAND PROVINCE

East of the Great Plains province lies another plains region that is distinctly lower than the first. Various names have been applied to it, but none seems better adapted to the region as a whole or more inclusive of the several topographically diverse subdivisions than the name used herewith—Central Lowlands. It is subdivided into several sections, but only the two that have Canadian extensions will be discussed in this paper. The first of these is the Western Lake section.

This section is irregular in shape and embraces a large part of the northern interior of the United States and a smaller part of south-central Canada. Its western boundary is the Tertiary erosion scarp (Missouri coteau) previously mentioned. The eastern boundary is also marked by a prominent topographic break throughout most of its length, and where a topographic separation is not easily made from the province next to the east there are good reasons for drawing the line empirically. The eastern boundary begins near Stillwater, Minnesota, and runs northwestward, skirting the Superior Highlands to Rainy Lake. From this point it continues north and west close to the eastern shore of Lake Winnipeg to a point near longitude 102°W. and latitude 55°N., where it closes with the western boundary. This line with minor exceptions is essentially the contact of pre-Cambrian rocks of the Laurentian Plateau with the lacustrine sediments of glacial Lake Agassiz.

An optional line might be run along the most prominent western beach of Lake Agassiz and continued along a series of water-worn cliffs of Cretaceous rock overlooking a region of Silurian bedrock and the alluvial sediments of the former lake. Collectively these cliffs are known as the Manitoba escarpment.[1] Eastward flowing streams have cut numerous deep valleys in this escarpment and have left the intervening remnants standing as isolated hills, the most prominent of which are the Pembina, Riding, Duck, and Porcupine mountains.[2] Beyond Porcupine Mountain there are no adequate data for drawing the line, and it might therefore be

[1] C. A. Young, *op. cit.*, p. 108.

[2] D. B. Dowling, *Geol. Survey Canada, Guide Book, No. 8*, Part I, p. 80.

placed arbitrarily at the contact of Cretaceous rocks on the west with Silurian rocks on the east, which is essentially the condition existing all along this boundary in Canada, if we neglect the vertical separation of the two systems of rocks at the escarpment. As thus drawn the line curves to the west and closes with the western boundary just north of the fifty-fourth parallel. This line has not been used on the accompanying map because it is desired to correlate this work as closely as possible with the most recent work on the physiographic divisions of the United States.[1]

The surface of this region consists largely of a monotonous flat plain covered by the deposits of glacial Lake Agassiz, which at its maximum extended from the latitude of the southern boundary of North Dakota to the northern boundary of Manitoba. The Winnipeg Lake System is a remnant of this great lake. Morainic ridges along the edges of till sheets, intermorainic tracts of rolling till plain, and level lacustrine tracts marking the sites of smaller glacial lakes are also prominent features. The topography may be described in summary as pre-eminently glacial, and the effects of the ice sheets are evident to even the most casual observer.[2]

Similar topographic conditions are found in the Canadian division. Here also the surface is gently undulating and everywhere covered by a veneer of drift which either obscures or accentuates an earlier relief. In southwestern Saskatchewan is the level floor of glacial Lake Saskatchewan, a large and probably short-lived contemporary of the smaller glacial lakes of the United States, such as Souris and Dakota. The valley of the Qu'Appelle, which is one of the several deep valleys cut during postglacial erosion intervals, marks the former course of the South Saskatchewan at the time when the northward flow of that stream was blocked by ice. It is analogous in several ways to the Missouri River.[3]

Though the present relief of this section is pre-eminently of glacial origin, it is really a product of both glaciation and preglacial erosion, and to a lesser extent of postglacial erosion. This region as well as the Great Plains to the west was probably peneplained, or at least subdued, in late Tertiary time. It was later

[1] N. M. Fenneman, *Ann. Assoc. Am. Geog.*, VI, pl. 1.

[2] J. E. Todd, *U.S. Geol. Survey, Bull. 144.*

[3] D. B. Dowling, *op. cit.*, p. 80.

uplifted and well dissected probably in a preglacial stage of the Pleistocene epoch. The driftless area of Wisconsin is generally assumed to represent a slightly modified form of the topography of that stage. Then followed the advances and retreats of four or more ice sheets, with the consequent modification of relief and drainage lines. Since the older drift was deposited, erosion has produced a complex system of valleys in places, and some of the larger streams have developed broad, flat bottoms. In the area covered by the later ice sheets, there has been but little modification of the glacial topography. The rivers have terraced the outwash deposits, but the majority of glacial features remain unchanged. In the Canadian division of this section the drainage lines are still badly disorganized.

THE EASTERN LAKE SECTION OF THE CENTRAL LOWLAND PROVINCE

This is a region of general plain aspect immediately adjacent to the Great Lakes. It is difficult to give an exact definition of it that is inclusive in a broad way of all its topographic features, and at the same time delimit it from neighboring regions of apparently similar features. Writers on the physiography of the United States generally agree that the region adjacent to the Great Lakes possesses distinct glacial features which are easily recognizable from whatever point of the compass it is approached; and although the adjoining areas to the north, south, and west were also glaciated, there is sufficient contrast between the morainic, marshy, lake-dotted surface that characterizes the Lake Region, and the *roche moutoné* surface of the Laurentian Plateau and the till sheets of the plains to the west and south, to justify making this region a separate section.

Within the United States this section is bordered by the Adirondack Mountains, the Allegheny Plateau, the till plains, the Wisconsin driftless area, and the Superior Highlands. This boundary is generally marked by topographic breaks. In places along the border of the Adirondacks the break consists of the contrasting topography of mountain and plain; along the edge of the Allegheny Plateau it is an erosion scarp; in still other places it is a difference in topography not always to be comprehended in a

single view, but none the less real on that account—the difference between a surface of morainic ridges and till sheets. The northern boundary begins near Fort William, Ontario, and in a general way follows the shore line of the Great Lakes to the vicinity of Kingston, Ontario, where it closes with the eastern and southern boundary. This boundary is placed at the contact of the pre-Cambrian bedrock of the Laurentian Plateau and the sediments of the glacial lakes. As drawn on the accompanying map it practically coincides with the Algonquin-Iroquois beach as mapped by Upham,[1] and Leverett and Taylor.[2]

This section has two well-defined types of topography. The first consists of lacustrine plains immediately surrounding the existing lakes and bounded in places by morainic ridges concentric with respect to them. These "lake plains" are built up of the sediments of glacial lakes that covered an area greater than the present lakes. They are in topography, age, and structure analogous to the lacustrine plains of the Western Lake region. A narrow strip of territory of this type extends around to the Canadian side of the Great Lakes.

The second type of topography embraces areas characterized by ground moraine, morainic ridges, swamps, and small lakes. These areas border the "lake plains" on the south and constitute by far the larger part of the section. Similar topographic features are found north of the Great Lakes, in fact, they are widely scattered over the Laurentian Plateau, but they are so decidedly subordinate to the features of the old erosion surface that no great difficulty is experienced in locating the dividing line between the two provinces. This second type of topography is particularly well developed in the peninsular portion of Ontario.[3]

Glaciation is of course the main topic to be discussed in the physiographic history of this section. All of the principal features of the topography are the results either of unequal glacial accumulation or of the alteration of drainage lines; and although preglacial topography probably conditioned results to some extent, it is now

[1] Warren Upham, *U.S. Geol. Survey, Mon. 55.*

[2] Frank Leverett and F. B. Taylor, *U.S. Geol. Survey, Mon. 53.*

[3] F. B. Taylor, *Geol. Survey Canada, Summary Report* (1909), pp. 164–67.

so nearly obliterated that history must begin with the surface changes of the Pleistocene epoch. These were the changes incident to the advance and retreat of several ice sheets. The United States and Canadian divisions of the section were similarly and contemporaneously affected. Post-Pleistocene history is largely a record of drainage readjustments following the final disappearance of the ice.

THE NEW ENGLAND PROVINCE

East of the Hudson-Champlain Valley and south of the St. Lawrence River lies the New England region. Physiographers regard it as a province in the major division of the Appalachian Highlands. It is bounded on the east by the Atlantic Ocean, and on the west by a line running north from Long Island Sound along the eastern border of the Hudson-Champlain Valley[1] to the foot of Lake Champlain, thence northeast to the city of Quebec and down the St. Lawrence Valley.[2] Newfoundland, though detached and separated from the mainland by a considerable body of water, is really an outlier of this province and will be treated as a section of it.

Exclusive of the coastal margin, New England topography is largely of the type of an uplifted, extensively dissected, and glaciated peneplain. To this general characterization, however, must be added certain modifications. Although the terms "upland" and "plateau" may be properly applied to the southern half, a part of the northern half is so mountainous as quite to conceal the plateau feature. The Connecticut Valley must also be considered as departing from the general characterization. The topography is controlled by three prominent structural features, namely: (1) a western mountain axis, extending through Connecticut, Massachusetts, and Vermont; (2) an eastern mountain axis, unimportant topographically in the United States, which runs from Rhode Island to the Maritime Provinces of Canada; and (3) a long, narrow, structural depression between these two axes, in part occupied by the Connecticut Valley.

Each of these mountain axes was early in geologic time a line of elevation. The northern part of each still retains the

[1] N. M. Fenneman, *Ann. Asso. Am. Geog.*, IV, 101–4.

[2] C. A. Young, *op. cit.*, p. 108.

mountainous character of the initial (or at least an early) uplift, but the southern parts were eroded to the condition of a peneplain, then elevated again and dissected.[1] Standing above the general surface of the uplifted peneplain are numerous residual mountain masses or peaks, typical of which are Monadnock and Katahdin.[2]

The Connecticut Valley, though a structural as well as a topographic depression throughout its entire length, also has northern and southern divisions of unlike characteristics. In this case, however, the contrast is not due so much to differential uplift or depression as to inequalities of hardness and resistance to erosion.

The general conditions just cited for New England are continued across the International Boundary into Canada. The Green Mountains of Vermont, the northern expression of the western axis, extend into Quebec under the name of the Notre Dame Mountains. They border the estuary of the St. Lawrence and continue into and through the Gaspé Peninsula, where they are known as the Shickshocks. The White Mountains of New Hampshire, the northern expression of the eastern axis, extend northeastwardly through Maine, close to the border of Quebec, and gradually blend with the elevated tracts of New Brunswick and the Maritime Provinces. "Though the general course of the hills of the Maritime Provinces parallels that of the Appalachians, the propriety of including the territory in the Appalachian region is better shown by the geologic features, such as the Appalachian folding, and by the pronounced northeastwardly trend of the whole Province of Nova Scotia, the parallel long indentation of the Bay of Fundy in the southeast and that of Chaleur Bay with the valley at its head in the northwest."[3]

The Appalachian part of Canada is generally regarded as having participated in the Jurassic-Cretaceous base-leveling, and locally at least in the Tertiary base-leveling. The accordance of summit elevations, particularly in the eastern portion, and the presence of isolated residuals rising here and there above the upland level indicate a former peneplain which probably correlates with the

[1] W. M. Davis, *Bull. Geol., Soc. Am.*, II, 557.

[2] J. H. Perry, *Jour. Geol.*, XII, 1–14.

[3] C. A. Young, *op. cit.*, pp. 30–32.

higher peneplain of the Appalachians in the United States. Sutton Mountain of the Notre Dames and many of the peaks on the Gaspé Peninsula are typical monadnocks. The Cobequid upland of Nova Scotia is compared by Bell[1] to the Unakas and its origin referred to the Cretaceous base-leveling, and the Cumberland lowland adjoining it is regarded by him as a local peneplain developed in Tertiary time.

Though cut off from the mainland, Newfoundland is really a structural and topographic subdivision of the Appalachian region. The uplands of Newfoundland are the remnants left by the dissection of a once almost perfect peneplain, and there is no more striking feature in its topography than the marked parallelism of its peninsulas, re-entrants, lakes, ridges, rivers, and outcrops, which in nearly every case approximates a direction of N.20°E.[2] The Shickshocks of the Gaspé Peninsula, after being interrupted by the depression of the St. Lawrence Valley, seem to be continued in the Long Range, a mountainous feature that parallels the entire western coast of Newfoundland. This range has an average elevation of about 2,000 feet and compares very closely in this respect with the Shickshocks. The Lewis Hills, apparently a residual mass lying half-way between St. George Bay and the Bay of Islands, rise to 2,700 feet. The elevated tracts of the Maritime Provinces also appear to be continued beyond the Gulf of St. Lawrence in a series of flat-topped hills, on which rise local elevations separated by long, parallel valleys.

On the side of the island that faces the gulf the youthful aspect of the streams, the numerous terraces rising like gigantic steps from 12 to 400 feet above high water, and the delta deposits at the mouths of the rivers indicate several recent stages of elevation; but on the seaward side drowned gorges and almost submerged islands testify to recent and progressive submergence. These conditions are suggestive of the conditions existing between northern and southern New England with respect to elevation and depression. Clark,[3] however, connects Newfoundland orogenically

[1] W. A. Bell, *Geol. Survey Canada, Guide Book, No. 1*, Part II, pp. 326–28.

[2] W. H. Twenhofel, *Am. Jour. Sci.*, Fourth Series, XXXIII, 1–24.

[3] J. M. Clark, *Geol. Survey Canada, Guide Book, No. 1*, Part I, pp. 93–95.

with the mainland only through the eastern axis, and he states that the western axis ends in an arc at the end of the Gaspé Peninsula.

The physiographic history of the New England region begins with the close folding that occurred near the end of the Pennsylvanian epoch. But although this folding controls the topography, the detailed forms so far as known are the net result of two periods of base-leveling and subsequent uplift, one in Jurassic-Cretaceous and the other in Tertiary time, modified by glaciation.

Of the history of the Canadian Appalachians, Goldthwait[1] says:

> During the closing part of the Mesozoic subaërial denudation seems to have held sway. The mountains were slowly but surely reduced to a plain of low relief or "peneplain." Locally, in districts remote from the coast and where stronger rock structure appeared just above the Cretaceous base-level, the reduction of the surface was incomplete and many residual mountains or monadnocks were left. On the whole, however, the base-leveling was very thorough, planing away the harder rocks as well as the weaker.
>
> This almost complete cycle of denudation was brought to a close at about the beginning of the Tertiary by regional uplift. The uplift seems everywhere to have been greatest in the interior and least near the coast. By it the seaward-flowing rivers were revived and a new cycle of erosion was begun, and by mid-Tertiary time broad lowlands had been developed. Another uplift occurred and the lowlands were carved by the streams until a fairly mature topography had been evolved beneath the Tertiary surface.

THE LAURENTIAN PLATEAU

Lying with its vertex near the Great Lakes a U-shaped area of pre-Cambrian rocks stretches away to the north, inclosing Hudson Bay in its arms, and extends into the still unexplored regions of the Arctic. It embraces nearly all of the northeastern part of North America and projects two spurs, the Adirondack Mountains and the Superior Highlands, into the United States.

The western and southern boundaries of this division have been described or have had their locations implied in previous paragraphs. The location of the northern boundary cannot be stated with accuracy, but may be placed tentatively near the sixty-eighth parallel. The northeastern boundary of the plateau proper is a group of mountains that lie close to the coast and extend from the

[1] J. W. Goldthwait, *Geol. Survey Canada, Guide Book, No. 1*, Part I, pp. 6–7.

Straits of Belle Isle northward through Labrador, Baffin Island, Devon Island, and Ellesmere Island to Cape Sabine, a distance of approximately 2,000 miles. The ranges of this group are truly mountainous, with known elevations of 6,000 feet or more and with peaks estimated to approach 7,500 feet.[1] Allowing even a wide latitude of topographic variation, such mountains could scarcely be considered an integral part of the plateau. In the absence of topographic data the line separating plateau from mountains can be conjectured only, and that within wide limits of error. From the Straits of Belle Isle the southwestern boundary is the Gulf of St. Lawrence and the estuary of St. Lawrence River. Within these boundaries the Laurentian Plateau may be considered to be a topographic unit. Its chief features are those of a peneplained region of crystalline rocks which was uplifted, extensively dissected by ordinary erosion processes in preglacial time, and more recently heavily glaciated.

The Laurentian Plateau has a gently undulating surface, diversified by such glacial features as moraines, lakes, swamps, muskegs, and outwash deposits. Over large areas a hill 150 feet high is a conspicuous feature of the topography, and though a few do actually approach 300 feet, they are of course residuals. The plateau is generally considered to be an uplifted peneplain, dissected to such a degree that it appears rough but not rugged. It should be borne in mind, however, as Adams[2] has pointed out, that the term peneplain is used merely as descriptive of the nearly level character of the country without any implication for a definite origin for it. Wilson[3] has called attention to the fact that it is not a single peneplain, but probably a series of facets produced in widely separated periods. Very few of the qualities of the typical peneplain are present. There are no deep residual soils; in fact, there is no continuous cover of soil, except in the southern part, and no well-organized drainage courses. Instead there is a maze of youthful streams and lakes, and in places the altitude reaches 2,000 feet. Unequal uplift and intense glaciation have so modified the topography that must have existed at the end of the erosion

[1] F. D. Adams in *Problems of American Geology* (Yale University), p. 45.

[2] F. D. Adams, *op. cit.*, p. 49.

[3] A. W. G. Wilson, *Jour. Geol.*, XI, 615–19.

interval preceding the glacial epoch as to make its general peneplain character recognizable only by the pronounced and uniform discordance between surface and geologic structure.

The southeastern border of the plateau, where it overlooks the St. Lawrence lowlands and the estuary of the St. Lawrence River, is more rugged and uneven than the remainder, and is known as the Laurentide Mountains. The greater ruggedness of this border is due not entirely to residuals that survived the base-leveling of earlier cycles, but to some extent at least to the greater uplift of the peneplain along this line. An observer on the highlands looks across a plateau-like surface, but one in the lowlands looks up against the scarplike face of a range of hills of sufficient height to be known as mountains. It has been suggested that this escarpment may mark the line of a fault or a series of faults.[1]

Tributaries of the St. Lawrence cross the Laurentide Mountains in deep, steep-sided canyons or gorges, which accentuate the ruggedness of the local topography. The Saguenay, the Coldwater, the Hamilton, and the Ottawa rivers are typical of this class, and in places their canyons are more than 2,000 feet deep. These canyons may represent ancient river valleys deepened by subsequent glaciation, or they may be of the "graben" type and similar to many of the streams of the Adirondacks.

The physiographic features of the Laurentian Plateau are reproduced in miniature in the Adirondack Mountains. There also is a plateau, nearly uniform in elevation, but rising to somewhat greater heights along the northeast, east, and southeast borders.[2] The plateau is apparently an uplifted peneplain. The rougher margins may have been base-leveled at the same time as the remainder, but if so all traces of the old erosion surface have been effaced in subsequent changes.

The drainage of the eastern Adirondacks is remarkably like that of the southeastern and eastern borders of the plateau proper. Many of the streams and lakes lie in steep-walled gorges or chasms. Escarpments produced by the compounding of several fault systems are also suggestive of the scarp along the border of the Laurentide Mountains.

[1] E. M. Kindle and L. D. Burling, *Geol. Survey Canada Mus., Bull. 18.*

[2] W. J. Miller, *N.Y. State Mus., Bull. 164*, p. 81.

The remainder of the Adirondack region, the western half or plateau portion, "is not absolutely flat, but is more or less diversified with low hills and intervening broad valleys. Occasional summits give views of moderate extent, but no elevations can properly be called mountains, and the general term plateau is most expressive."[1]

In the Superior Highlands of northern Wisconsin, northwestern Michigan, and northern Minnesota there is another area topographically similar to the Laurentian Plateau proper.

> Like the latter its sky line is distinctly even and gives little hint of the mountainous structure that prevails almost everywhere within it. Its principal topographic feature is an uplifted and dissected plain of erosion which has been glaciated and hence has many secondary features due to ice erosion. It lies neither in the region of pronounced glacial aggradation nor in that of intense glacial denudation; hence those forms that are of glacial origin are due in some cases to ice scour, in others to ice accumulation. A certain amount of glacial detritus occurs here and there; in other places the surface is swept practically clean by glacial erosion. The glacial material is irregularly disposed in characteristic fashion and blocks the drainage to such an extent that ponds and lakes occur in large numbers.[2]

The Laurentian Plateau with its outliers or spurs is an ancient peneplain which has undergone differential elevation, has been denuded, subsequently dissected around the margins, and extensively glaciated. Further than this little may be said regarding its physiographic history. It is fairly well established that a peneplain was developed in pre-Cambrian time over the main part of the plateau, including the Adirondacks and probably the Superior Highlands. There is some evidence of a second peneplain developed upon Paleozoic sediments. Owing to the almost complete removal of these sediments and their existence at present only in small down-faulted blocks, the fact of this peneplain is not fully established. There is unquestionable evidence of a third, probably Cretaceous, peneplain produced over the greater part of the plateau, including the Adirondacks and possibly the Superior Highlands. However, in the present state of our knowledge, sweeping generalizations regarding the number, dates, or extent of the several peneplains are not justifiable.

[1] J. F. Kemp, *Pop. Sci. Mon.*, LXVIII, 199.

[2] Isaiah Bowman, *Forest Physiography*, pp. 572, 573.

THE ST. LAWRENCE VALLEY PROVINCE

The St. Lawrence Valley, bordered on one side by the New England region and on the other by the Laurentian Plateau, is a strip of territory sufficiently different in structure, topography, and physiographic history to require separate discussion. This is known to Canadian geologists as the St. Lawrence Lowlands. This name is perhaps better suited to designate the province than St. Lawrence Valley as the province has a greater extent than the mere valley of the river.

Commencing near the city of Quebec, these lowlands stretch on both sides of the St. Lawrence River, southwestward, with slightly diverging boundaries until at Montreal the level country is approximately 120 miles wide. Beyond Montreal the northern boundary pursues a westward course up the Ottawa Valley to a point about 50 miles beyond Ottawa city, where a ridge of broken country, a low spur of the Laurentian Highlands, projects southward, crossing the St. Lawrence between Brockville and Kingston to join the elevated Adirondack region of northern New York.[1]

Young extends the province beyond this spur and includes the territory of the Ontario Peninsula "lying between Lakes Huron, Erie, and Ontario, and bounded on the north by a nearly east-west line from Kingston to the foot of Georgian Bay." In this paper this territory has been included in the Lake section, and the Laurentian spur should probably be regarded as the natural boundary of the lowlands. This opinion is supported by Kindle and Burling, who write that "the Paleozoic plain of the Ottawa and St. Lawrence valleys lies between the Laurentian Plateau on the North and the Adirondack uplift on the South, and extends eastward from the Archean shield at the head of the St. Lawrence to the zone of Appalachian folding east and southeast of Montreal."[2]

Branching off to the south from this province near Montreal is the Champlain-Hudson Valley, which is topographically similar to the St. Lawrence Valley and which may be regarded as a section of the province.

The main division of the province, that which embraces the valley of the St. Lawrence River, is a plain floored with Paleozoic

[1] C. A. Young, *op. cit.*, p. 60.

[2] E. M. Kindle and L. D. Burling, *op. cit.*, p. 9.

rocks. Its elevation is but a few hundred feet above sea-level, and there are only occasional departures either upward or downward from the general level. It lies beneath the limiting provinces and is cut off from two of them by faults—the St. Lawrence-Champlain fault separating it from the New England region,[1] and the Laurentian Plateau fault marking its northern boundary.[2]

Of the few eminences rising above this plain, the Monteregian Hills are the most prominent. These hills are eight in number. They extend along an east-west line about ten miles apart, and rise abruptly from 600 to 1,200 feet above the surrounding country. Structurally they are cores of igneous rocks (probably conduits emanating from a dike or laccolith) surrounded and mantled by sediments in such a manner as to indicate that at the time of their intrusion the overlying Paleozoic strata were many hundreds of feet thicker than at present. This great mantle of rock has been since removed by erosion, except where local down-faulting has preserved remnants of it. Recent work on the Laurentian Plateau has discovered several outliers of Paleozoic rock scattered over its surface which were preserved in this manner.

A variable thickness of glacial material which was assorted by the Pleistocene or post-Pleistocene marine invasion is spread upon the Paleozoic bedrock. Upon this in turn lies a thin veneer of marine sediments. The earlier erosion topography is probably neither accentuated nor subdued in any marked degree by the drift and sediments.

The Champlain-Hudson Valley resembles the St. Lawrence Valley in several respects, namely, it lies at approximately the same altitude above sea-level; it is a low plain lying between adjacent mountainous provinces; it is floored with Paleozoic rocks; it has a mantle of drift spread over an old erosion surface; and it was subjected to a postglacial marine invasion. A part of this valley is occupied at present by the waters of Lake Champlain and Hudson River.

In the St. Lawrence Valley physiographic history begins with the emergence of the Paleozoic rocks with which it is floored. The

[1] C. A. Young, *op. cit.*, p. 62.

[2] E. M. Kindle and L. D. Burling, *op. cit.*, Fig. 5.

time of this emergence is uncertain, but post-Devonian at all events, as deposits containing Devonian fossils have been found in places. These sediments were probably 5,000 feet thick over the province at the time of the emergence, and no doubt they also covered a part of the Laurentian Plateau and the Adirondack Mountains.

From the time of the emergence until the Pleistocene epoch erosion appears to have been uninterrupted, and the region was denuded of 2,000 to 3,000 feet of rock. This almost completely uncovered the pre-Cambrian rocks of the plateau, and would have exposed the pre-Cambrian in the St. Lawrence Valley had not down-faulting on a large scale preserved a variable thickness of the sedimentaries.[1]

During or immediately preceding the Pleistocene epoch there was a widespread downwarping of central and eastern Canada, which caused the former southward-flowing streams to change their direction of flow to the north. As the ice retreated, some of the water found an outlet to the sea via the St. Lawrence River and distributed along its course a considerable amount of glacial débris. When the ice had retreated far enough, the sea advanced up the St. Lawrence Valley, assorted the glacial material by wave-action, and deposited upon it a thin bed of marine formation. With the final disappearance of the ice there was a general elevation of the north country, and marine beds are now found in certain places at elevations exceeding 600 feet.[2]

The Champlain-Hudson Valley was the scene of a similar sequence of events, as witness the character of the bedrock on the valley floor, the assorted glacial débris, and the postglacial marine beaches standing 300 or more feet above sea-level.[3]

[1] E. M. Kindle and L. D. Burling, *op. cit.*, p. 20.

[2] J. W. Goldthwait, *Geol. Survey Canada, Guide Book, No. 3*, pp. 118–26.

[3] W. J. Miller, *N.Y. State Mus., Bull. 168.*

THE GEOLOGY OF THE KILLDEER MOUNTAINS, NORTH DAKOTA

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The physiography of the Killdeer Mountains illustrates a case of rejuvenation without uplift. The drainage was rejuvenated by the deflection of the Little Missouri River due to the approach of an ice sheet. The deflection, which brought the Little Missouri River much nearer the mountains than it was before, produced a great increase in the gradient of the mountain streams.

A study of the rocks extends the known distribution of Oligocene formations in the Northwest. Much of the rock is limestone, and the formations appear to have been made by wind, river, and lake actions.

LOCATION AND DESCRIPTION

The Killdeer Mountains are in the western part of North Dakota, about halfway between Manitoba and South Dakota, and 50 miles east of the Montana line. They are part of the watershed between the Missouri and Little Missouri rivers, the watershed extending 250 miles southward to the Black Hills. The mountains consist of two mesas, called North Mountain and South Mountain, which are surrounded by cliffs which in some places are more than 100 feet high. The mountains cover an area of about 10 square miles, but they are so deeply cut into by streams that the plateau tops are less than 2½ square miles in area, and the periphery of the plateaus is about 30 miles. Most of the mountain area consists of slopes covered with talus and landslides, deep, wide valleys, and foothills characterized by decapitated slopes. Here and there steep-sided peaks rise from the plateaus, the highest being about 3,200 feet above sea-level, and about 150 feet above the plateaus. The mesa tops, which are upheld by a series of interstratified sandstone and limestone layers, are about 500 feet higher than the plains.

PHYSIOGRAPHY

Character and growth of the valleys.—The areal distribution of valleys in the Killdeer Mountains is relatively large. The main valleys are wide-mouthed, steep-sided, and nearly flat-bottomed. Numerous short, steep-sided gulches cut into the level upland. The slopes of the main valley floors are gradual because they are in uniformly soft clay and sand formations; but the heads and sides of the valleys are steep because they are bounded by the resistant interbedded limestone and sandstone in the upper part of the plateaus. The gulches and valley heads are still in infancy, whereas the lower valleys are farther along in their work of lowering the valley floors to the level of the plain. The valley floors are strewn with masses of resistant rock from the upper slopes. In some places the beds of the upper slopes have slipped down from their original position in such a way that they retain their horizontal position, although about 100 feet below the level in which they were in place. In some places streams have cut their way in behind the slump, thus increasing the slump by continually undercutting the already sliding cliff face. In some cases the slumps were started by the formation of caves. Several of these caves have the position of fissures, but their size and their irregular shape and the high lime content of the rock show that they were enlarged, at least, by solution. Nearly parallel to the south-facing cliff of South Mountain, near Oakdale, there is a cave opening known as Medicine Hole, which gives access to a crack at least 90 feet deep and a score or more feet long. This opening cuts through the limestone formation which caps that part of the mesa, and the bottom of the aperture is in the weak sand formation. Less than 100 feet south of the fissure is the cliff face of the upper hard ledge. As soon as this ledge is undermined a little more the separated mass will slump.

Spurs.—The advance of the valleys has left little but the spurs of what was once a much larger mountain. The spurs are long, skeletal, and straggling. Perhaps the most striking spur is the southeastern end of the South Mountain, just above Oakdale, but the southwestern end of the mountain is also notable (Fig. 1). It is almost a semicircle, half a mile in periphery, with precipitous inner walls. Below the cliffs lie benches and hollows due to land-

slips. The map shows that almost nothing of the mountains remains but spurs. If the contour intervals were smaller they would show that the slopes are benched on account of the varying hardness of the rock layers. There are three main benches, which are caused by hard layers referred to in the rock section as the lower, middle, and upper hard ledges, respectively. All the benches show as outcrops in the picture of Indian Knob.

Work of the wind.—At the base of thick resistant layers the wind has undercut the cliff as much as six feet. Undermining of the

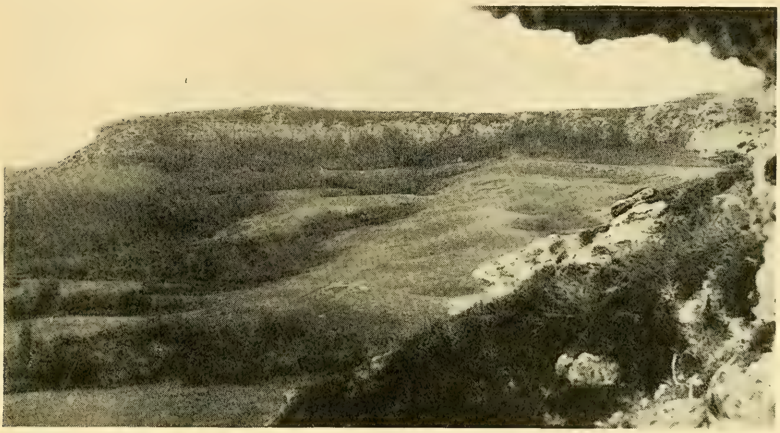

FIG. 1.—Southwest spur of South Mountain. It is almost a semicircle, half a mile in periphery, with precipitous inner walls, and landslide topography below.

resistant layers causes the overhanging mass to be held in place by the shearing strength of the rock. If there were caves along the zone of stress, rupture would be likely to follow the plane of weakness. The layers of interstratified sand and limestone show the wind's work. The wind has scooped out the sandstone for eight or nine inches, leaving layers of the limestone projecting to this extent. In a less arid and less windy climate these conditions might be reversed.

Work of running water.—Charlie Bob Creek on the northwest, and Jim Creek on the northeast, both tributaries of the Little Missouri, are the chief agents of erosion. The tributaries of the Missouri River, particularly Knife River and its tributary, Spring

Creek, drain the mountains to the south and southeast (Fig. 2). From a distance the mountains appear to slope toward the north and northwest in long, smooth plains. Closer inspection, however,

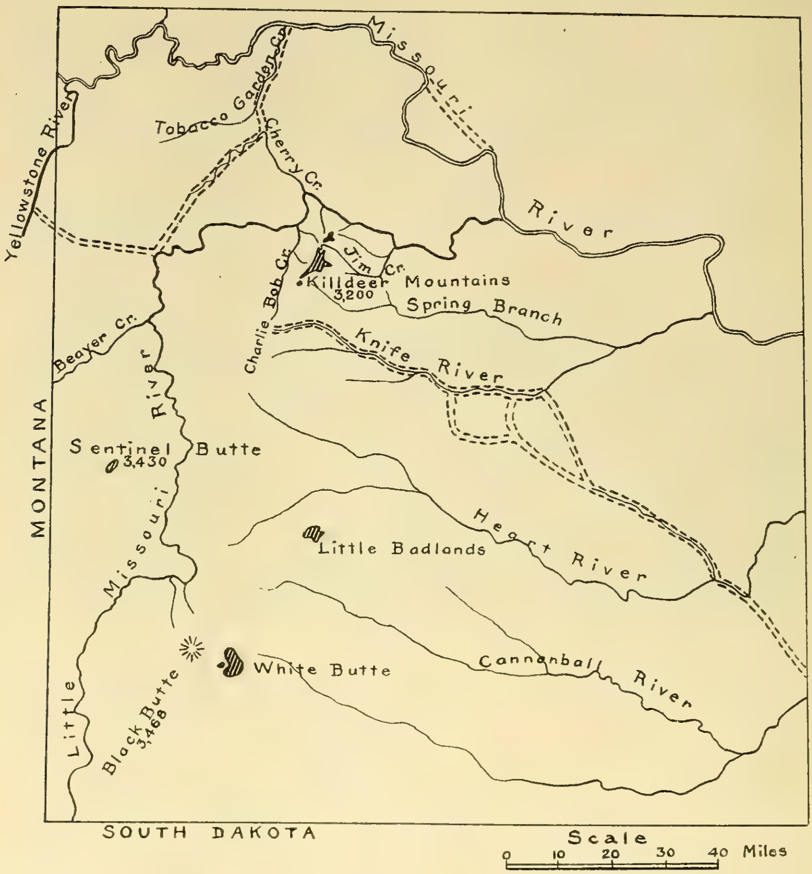

FIG. 2.—Map showing the distribution of the White River formation (shaded) in North Dakota. Abandoned Pleistocene channels are indicated by dashes. (After Leonard.)

shows that these slopes are fragmentary, and that many are decapitated by the tributaries of the Little Missouri River. These creeks have extended their heads westward through the gap between the mesas, so that in some places parts of two drainage systems

may be seen: west of the gap uplands sloping to the west and streams flowing to the east, and east of the gap eastward flowing streams and remnants of an eastward sloping upland. The streams flowing northward likewise have cut into these long slopes, but since the heads of the streams have been working toward the south the action has been less effective, for direction of slope in this region makes a great difference in the rate of erosion. On steep, south-

FIG. 3.—Indian Knob. This picture illustrates the withering effect of the sun's strength on the south slopes; it shows also the three hard ledges.

facing slopes in western North Dakota grass scarcely starts before the intensity of the sunshine and the shallowness of soil cause it to wither. On north-facing slopes the difference is remarkable, the lesser heat of the sun permitting a luxuriant growth of grass and several varieties of trees. Trees grow on the northward facing slopes to the top of the divides, but on the mountain top and on the southern slopes, outside of sheltered valleys, there are no trees. Indian Knob (Fig. 3), a conical hill on the southern border of the mountains, illustrates the effect of the sun. The south side is bare and precipitous; the north slope is clothed with brush to the very top. With little or no vegetation to hold the soil on the south

slopes erosion is much more rapid than it is on the north. Thus it is that streams which work their heads toward the north erode more rapidly than those which flow northward.

Rejuvenation of the drainage.—The north and northwest drainage down the upland slopes interosculates with the heads of the eastward flowing tributaries of Jim Creek, which have worked their way round North Mountain both to the north and to the south. They have cut off the heads of the upland slopes, leaving them separated from the mountain tops, stranded remnants of an older drainage system. This is indicated in Fig. 4. At present the chief agent of erosion is the Little Missouri River, whose tributaries have a maximum fall of 1,200 feet in 6 miles. The upland slopes show that there were once streams with a gradient much less steep. Previous to some pre-Wisconsin ice invasion, probably Kansan,[1] the Little Missouri River entered the Missouri through the valley of Tobacco Garden Creek[2] (Fig. 2). The ice sheet ponded the waters of the Little Missouri, Yellowstone, and Missouri rivers, and caused them to overflow to the southeast. After the retreat of the ice sheet the Little Missouri River did not return to its old course, but flowed eastward, north of the Killdeer Mountains, across the divide between its old course and the Missouri. This change rejuvenated the drainage of the Killdeer Mountains. The present surface of the valley now occupied by upper Cherry Creek and Tobacco Garden Creek is about 150 feet above the present level of the Little Missouri River channel, and that valley is 30 miles farther away from the mountains than the Little Missouri. Thus, before the glacial period, the Killdeer Mountains were not being eroded so rapidly as now, because the gradient of their drainage system to the northwest was only about 1,050 feet in 36 miles in place of 1,200 feet in 6 miles, 29 feet per mile in place of the present 200 feet per mile. The captured streams and numerous decapitated slopes about the Killdeer Mountains resulted from the Little Missouri River being turned by the glacial invasion from its

[1] A. G. Leonard, *Quar. Jour. Univ. North Dakota*, VII (1917), 233.

[2] Frank A. Wilder, *Geol. Surv. North Dakota, 3d Bien. Rpt.* (1904), p. 119. Also *U. S. Geol. Surv. Water Supply and Irrigation Paper 117* (1905), p. 43. A. G. Leonard, "Pleistocene Drainage Changes in Western North Dakota," *Bull. Geol. Soc. America*, XXVII (1916), 302.

northward course along Tobacco Garden Creek to its present eastward course 6 miles north of the Killdeer Mountains.

Stream piracy.—Formerly the divide between the Missouri and the Little Missouri rivers followed the long axis of the Killdeer

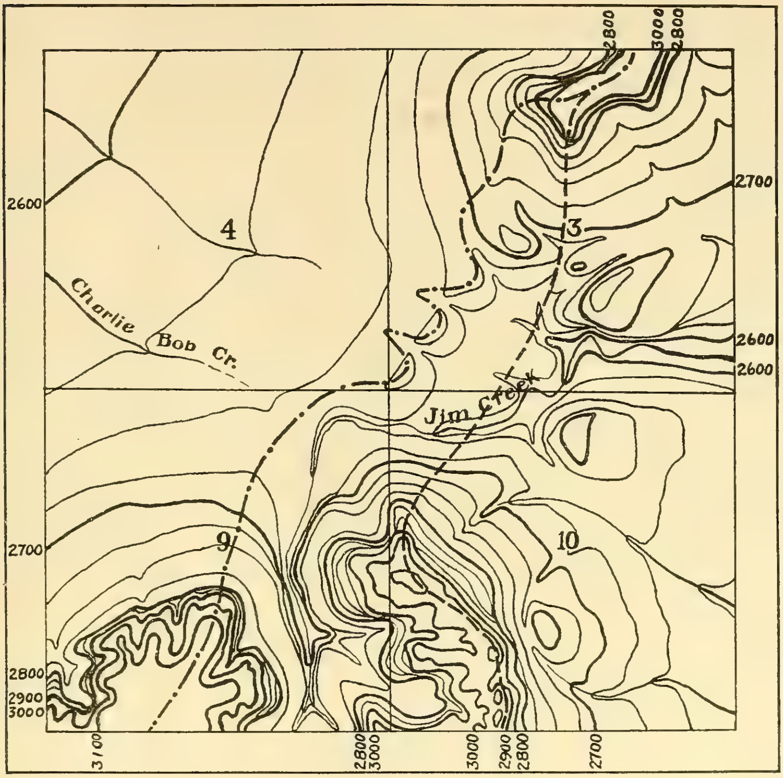

FIG. 4.—A representation of the change in a divide due to rejuvenation. The line of dashes denotes the position of the old divide between the Missouri and Little Missouri rivers. The dots and dashes indicate the present divide between two tributaries of the Little Missouri River. Note capture of the head of Charlie Bob Creek by Jim Creek, and the gorge cut in the old valley floor.

Mountains from north to south; now it passes along the south stretch of the South Mountain from west to east. The maps (Figs. 2 and 5) show what a considerable amount of stream capture attended the change. That part of the Little Missouri River


A RECONNAISSANCE MAP
OF THE
KILLDEER MOUNTAINS
DUNN COUNTY
NORTH DAKOTA
R 96 W.
T. 147 N.
T. 146 N.
Badlands
North Mountain
The Gap
Former divide
Jim Creek
South Mountain
Tributaries of Charlie Bob Creek
Tributaries of Jim Creek and of the Little Missouri River
Tributaries of Charlie Bob Creek
Oakdale
Present divide
Dead Mans Gulch
Indian Knob
Tributaries of the Missouri River
Spring Branch
Legend
Oligocene formation
Fort Union formation
1 Mile
Contour interval 100 feet
Datum is sea level
1913
True North
N
Dotted contour lines are not accurate; they are sketched in for the purpose of indicating the character of the topography of the plains
Present and former divides are indicated by full and broken lines

FIG. 5

which flows east follows probably the valley of a smaller tributary of the Missouri. Jim Creek, a tributary of the Little Missouri River, captured the head waters of Spring Creek, a tributary of the Missouri. Then the captured additions of Jim Creek pushed back into the gap between the two mountains until they cut off the head waters of Charlie Bob Creek, a fellow-tributary of the Little Missouri River. Fig. 4 shows the change in the divide between North and South mountains, and the change in the

Fig. 6.—View from the northeast end of South Mountain, looking toward North Mountain. A vertical line through the center of the picture indicates the locus of the old divide. Compare with Fig. 4, and note the decapitated slopes.

course of the creek which flows from the north valley of South Mountain.

Origin of the mountain features.—The character of the topography proves that the Killdeer Mountains are relict mountains greatly dissected by the ordinary agents of erosion. The rock strata are flat-lying and of unequal resistance. There are three strong layers which have given rise to the plateau tops and to two benches, one preserved only in the peaks, and one below the main table-land (Fig. 6). The decapitated slopes and the cases of stream piracy were caused by rejuvenation of the drainage due to a post-Kansan change in the course of the Little Missouri River.

STRATIGRAPHY

The geologic formations which compose the Killdeer Mountains are of Cenozoic age. The whole of Dunn County is underlain by the Fort Union formation of the Eocene system; the upper 400 feet of the strata forming the mountains is here referred to the White River formation of the Oligocene system.

Fort Union formation.—In the region of the Killdeer Mountains the lower strata belong to the upper part of the Fort Union formation. In general these beds differ from the lower members of the same formation by their darker color. As Leonard says, "The upper beds are composed of rather dark gray sandstone and shale, with many brown, ferruginous, sandy nodules and concretions."[1] The beds are of possible value by reason of lignite and beds of high-grade, white, plastic clay.[2] Other characteristics of these members of the Fort Union formation are carbonaceous shales, nodular ferruginous concretions, and many selenite crystals in beds of clay and shale.

White River formation.—In contrast to the dark color of the upper Fort Union formation the southern exposures of the Killdeer Mountain sides are as white as chalk. Throughout the entire thickness of 400 feet of the upper strata there is scarcely a trace of carbonaceous material, especially no lignite. The clays are calcareous and low in plasticity. Unlike the firm-grained, compact fire clays of the Fort Union formation, the clays are crumbly in texture and so loosely packed that some are porous. Limonitic coloring and concretions, common in the Fort Union beds, are rare in the upper strata. The small amount of iron present is in the ferrous form, tinging the rocks pale green. Certain hard sandstones and some of the clays and coarse sands are dark green. There are several layers of limestone, whereas, save for a few thin beds, limestone has not been reported as a phase of the Fort Union formation in North Dakota.

The outcrops on the mountain sides are few and nowhere continuous from the bottom to the top. Fossils are either very rare

[1] A. G. Leonard, *Geol. Surv. North Dakota, 5th Bien. Rpt.* (1908), p. 45.

[2] E. J. Babcock and C. H. Clapp, *Geol. Surv. North Dakota, 4th Bien. Rpt.* (1906), p. 132.

or wanting in these deposits, none being found in spite of diligent search. Only three places were found where the contact between the Fort Union formation and the beds above is exposed. A discrepancy of 41 feet between the elevations of these places shows that the contact is uneven. Furthermore it is apparent that the Fort Union rocks were oxidized and eroded before the deposition of the basal unoxidized stratum of the overlying formation.

A generalized composite section of the younger formation, worked out from eight partial sections, is as follows:

WHITE RIVER FORMATION, KILDEER MOUNTAINS, NORTH DAKOTA

7. Pale-green, fine-grained, calcareous sandstone, interstratified with subordinate amounts of marl, hard layers of white limestone, and lenses of green, cherty sandstone. 97 feet.

6. Upper hard ledge, a layer of ash-gray, arenaceous limestone. In the southern part of the mountains there are green, cherty lenses and layers of quartzite within this calcareous member. 6 feet.

5. Chalklike, soft, arenaceous marl. 64 feet.

4. Middle hard ledge, upholding the main plateaus. Greenish-gray, white weathering, interstratified limestone and friable sandstone. Rootlike stringers of white calcium carbonate join the layers of limestone through the sandy layers. In the north part of the mountains the ledge is almost solid limestone; in the southern outcrops the rock is sandy, porous, and apparently made up of grains of limestone and silica. 30 feet.

3. Pale-green, friable, cross-bedded sandstone. In the southern outcrops it appears to be wind laid, but at the north end there are several layers of limestone with the sand. 30 feet.

2. Lower hard ledge, a layer of pale-green, fine-grained, calcareous sandstone, much like the middle hard ledge, but it is limestone near the north end of the mountains. 10 feet.

1. Green, crumbly, non-plastic clays, and green, fine and coarse, uncemented sands. At the southern end of the mountains there is a pebbly conglomerate layer one foot thick near the base of the member, and in a calcareous phase there are pebbles of limestone, quartz, and granite scattered sparsely throughout the rock. 170 feet.

Total thickness about 400 feet.

Most of the rocks are water laid, but part of member No. 3 is Eolian. The rocks are characteristically loosely cemented and very friable, but some of the sand is indurated to quartzite. The cement is chalcedonic and opaline quartz. Many pieces of opal were found; some are transparent and very pale blue, others are milky white, and a few are dark brown with white streaks resembling the grained appearance of silicified wood.

The limestone layers are all siliceous, the silica being in very fine grains. Some of the limestone is clearly clastic in character, the constituent grains being distinguishable by the naked eye. One specimen of limestone taken from the upper hard layer contains 47.7 per cent $CaCO_3$, but the sand content lowers the amount of $CaCO_3$ below this figure in most of the rock.

The clays are characteristically pale green or pink, loosely granular in texture, and but slightly plastic. When a piece of the green clay is dropped into water it falls into fragments. Within a minute after a small piece is put into water it has disintegrated into very small flakes which have the appearance of a green, flocculent precipitate. When made into stiff mud and used as a plaster the clay hardens on drying and serves the people of the district in place of lime. Although they call it "natural lime" and use it for many purposes, even in place of putty to fasten glass in window sash, as mortar, and as a wall wash, the rock contains less than 2 per cent lime.

Correlation with White River deposits.—These rocks are unconformable on the Fort Union formation. The only sedimentary beds which are known to lie on the Fort Union formation in North Dakota belong to the White River formation. These beds are White Butte, Little Badlands, and Sentinel Butte deposits, all of which are similar to the Killdeer beds. White Butte deposits near Sandcreek post-office, Billings County, were discovered by Cope in 1883. He wrote: "The beds, which are unmistakably of the White River formation, consist of greenish sandstone and sand beds of a combined thickness of about 100 feet. These rest on white calcareous clay rocks and marls of a total thickness of 100 feet. These probably belong to the White River epoch, but con-

tain no fossils."[1] From the upper beds Cope collected several fossils of vertebrates, including species of Aceratherium and Oreodon. Leonard describes these beds as "conspicuous, snow white elevations."[2] Further he continues: "The White River group is here composed of white clays at the bottom, on which rests a coarse sandstone which in places is filled with large pebbles; this is overlain by about 100 feet of calcareous clays which in turn are overlain by more than 100 feet of fine-grained, greenish sandstone." From the calcareous clays he reports the finding of an Eporeodon major skull. Earl Douglass[3] reports Mesohippus, Aceratherium, Ictops, and Merycoidodon fossils from the beds at White Butte. The remains are fragmentary and scarce, but enough fossils have been found to place the beds without question in the White River formation.

In the same report Douglass reports Oligocene strata at the Little Badlands 26 miles northeast of White Butte and about 14 miles southwest of Dickinson. The section of the beds which he gives is similar to that of White Butte; there also he found enough fossils to identify the beds as of the White River formation.

The strata at the top of Sentinel Butte belong probably to the Oligocene series. They are composed of light-gray calcareous clay or marl, which contains toward the top beds of a nearly white, compact limestone. These beds contain fossil fishes which are not closely related to any previously described; therefore, by means of these, Plioplarchus whitei Cope, and Plioplarchus sexpinosus Cope, no correlation is possible.[4] Sentinel Butte is about 40 miles west of northwest of the Little Badlands and about the same distance north of northwest of White Butte (Fig. 1).

The Killdeer Mountains are about 50 miles northwest of Sentinel Butte and about 45 miles north of the Little Badlands. Sentinel Butte is part of the divide between the Little Missouri River and its tributary on the west, Beaver Creek; with one exception it is

[1] E. D. Cope, *Proc. Amer. Phil. Soc.*, XXI (1883), 216-17.

[2] A. G. Leonard, *Geol. Surv. North Dakota, 5th Bien. Rpt.* (1908), p. 65.

[3] Earl Douglass, *Annals Carnegie Mus.*, V, Nos. 2 and 3 (1909), pp. 281 ff.

[4] C. A. White, *Amer. Jour. Sci., 3d Ser.*, XXV (1883), 411-16; A. G. Leonard, *Geol. Surv. North Dakota, 5th Bien. Rpt.* (1908), p. 64.

the highest point in the state, being 3,430 feet above sea-level. The other known remnants of the Oligocene formations lie near the top of the divide between the Little Missouri River and the eastward flowing tributaries of the Missouri. Starting at the Black Hills, South Dakota, and following the divide north one comes to the White River formation first in Slim Buttes, then 20 miles farther north in the Cave Hills[1] deposits, which are only about 40 miles south of the White River strata on White Butte.

If one were to look for another remnant of the Oligocene beds to the north of the Black Hills he would continue logically in the direction of the known deposits, along the divide just outlined. If the Oligocene deposits once extended over the Killdeer district the elevation of these hills is such that they might well contain remnants of these deposits. The Killdeer Mountains are about 3,200 feet high and contain a thickness of almost 400 feet of Oligocene-like beds. The beds on Sentinel Butte at an elevation of 3,340 feet are only 40 feet thick. The thickness of the White Butte and Little Badlands deposits at lower elevations are about 320 and 200 feet respectively. A still greater thickness of Oligocene deposits at the Killdeer Mountains is explained by the general northeastward dip of the Fort Union strata north of Dickinson, North Dakota.

Because the deposits of the Killdeer Mountains are unconformable on the Fort Union formation, because they are similar in character to undoubted deposits of the White River formation less than 50 miles distant, and for physiographic reasons they are referred to the White River formation.

Origin of the White River deposits.—Professor Cope[2] wrote of the discovery of the White Butte deposits as "the locality of a new lake of the White River epoch." Todd[3] considers the White River beds of South Dakota to be lake deposits. Earl Douglass says:

> I have little doubt that the upper Tertiary deposits in North Dakota were also deposited in broad valleys of erosion. Much of the material of the deposits came from areas of granite and quartzite rock. In the region of the Black Hills are the only outcrops of these rocks for hundreds of miles; this, connected.

[1] J. E. Todd, *Geol. Surv. South Dakota, Bull. No. 2*, p. 123.

[2] E. D. Cope, *op. cit.*, p. 216. [3] J. E. Todd, *op. cit.*, p. 60.

with the fact that a series of remains of Oligocene deposits have been observed to extend from Dickinson to the Black Hills, suggests the probability that a river formerly flowed from the Black Hills northeastward through this region. If this be true, there should be coarse sediments as the mountains are approached, which is probably the case. Another thing which tends to confirm the idea that these are river valley deposits is the fact that, scattered over the plains, there are buttes apparently as high as White Butte, but which are not capped by later Tertiary beds.[1]

However, the apparent anomalous deposition on White Butte is explained by Leonard in another way:

> The beds of the White River group are wanting on Black Butte, although occurring at a considerably lower level only three miles to the west. In White Butte they are, however, found resting directly upon the thick upper sandstone of the Fort Union, which outcrops at several points near the base of the western slope of the western ridge, and also at its northern end. This sandstone here dips strongly to the east, so that within a distance of three miles its dip carries it from the top of Black Butte to the bottom of the ridge on the opposite side of the valley, where it is over 200 feet lower.[2]

It is believed that the beds on Sentinel Butte are lake deposits, and that some at least of the beds on White Butte are river deposits, especially the pebbly conglomerates.

At the Killdeer Mountains the greater part of the deposit is distinctly lacustrine, but some of the layers are wind worked. At the southwestern corner, however, on the south side of South Pass in the SW. ¼ Sec. 31, there are various remnants that suggest a river inlet. On the south face of this isolated hill there is an outcrop of coarse, yellow sandstone which is interbedded irregularly with bright-red, hematitic sandstone. It shows interrupted deposition by cross-bedding and lenses. This coarse sandstone is about 15 feet thick, covered by finer, more loosely cemented, pale, yellow-gray sandstone. It is a small outcrop, extending about 200 feet and abruptly ceasing. Above the sandstone there are water-worn pebbles, as large as three inches in length, scattered over the surface. These were traced back into heavy limestone masses, which show pebbles widely scattered on weathered surfaces. In a few places there is a thin ledge of very coarse sandstone carrying small pebbles;

[1] Earl Douglass, *op. cit.*, p. 288.

[2] A. G. Leonard, *Geol Surv. North Dakota, 5th Bien. Rpt.* (1908), pp. 65-66.

there is also a soft, sandy limestone of loose texture carrying gravel. Similar pebbles and residual masses of limestone were found out of place on the lower slopes of the south side of Indian Knob, but the pebbly limestone could not be traced back to the rock still in place. Also, on the south side of North Mountain a few scattered pebbles of the same general description were found, but again none could be found in place. The pebbles are of quartz and igneous rocks, with many limestone pebbles, some of which are pale green in color. It is conceivable that some of these pebbles were carried into the region where limestone and fine material were being deposited by cakes of ice or in the roots of floating trees. But at the southwest end of the mountains the abundance of the gravel leads to the supposition that at that place there may have been the debouchure of a river emptying into a lake. Furthermore the lower hard ledge does not continue distinctly in the southwest end of the mountains, whereas in the northern part it is almost solid limestone. From the fact that the limestone is more pure in the north end of the deposits it is argued that that end was farthest from the entrance of the river. Another item to support the supposition that the material was brought by rivers from the south is the fact that the gravels in White Butte are much coarser than any which have been found 100 miles farther north in the Killdeer Mountains. If it is argued that these deposits were laid down in small lakes connected by a single river, it should be remembered that gravel could not have been carried through one lake and on to deposition in the next. And as there is gravel in the deposit in South Dakota, again 50 miles farther north in White Butte, and again 100 miles farther north in the Killdeer Mountains, it must be supposed that the gravels were already distributed along the course of the river by some earlier and uninterrupted stream. This accords with Douglass' theory that the Oligocene deposits are in the channel of an earlier river.

The alternate hypothesis is that only the lower beds represent the work of a river, and that the upper beds, which are free of gravel deposits, were formed in a lake which overlapped the river deposits. The scattered outcrops of Oligocene deposits are explained better as the remnants of an almost eroded formation than as deposits

of different lakes joined by a river or rivers, for the deposits are found only near the top of the divides. They were once probably continuous and widespread. Furthermore the major part of the Killdeer deposits are of fine materials derived from a basin rich in limestone. The fineness of the materials betokens long transportation and thorough sorting, for the gravels are found only in the lower strata and only near the southern part of the deposits. The limestone layers are mechanical rather than chemical or organic deposits. The stream supplying the Oligocene lake must have been rather swift to carry so much calcareous and siliceous mud, and it must have come, without passing through any settling ponds, directly from the limestone highlands in the south.

CONCLUSION

The Killdeer Mountains are relict mountains on the divide between the Little Missouri and the Missouri rivers. They are deeply dissected by the tributaries of the Little Missouri River. Erosion has been hastened by the rejuvenation of the drainage due to a change in the course of the Little Missouri River. The change was caused by the advance of a pre-Wisconsin ice sheet, probably Kansan. The change increased greatly the gradient of the streams flowing from the mountains and gave rise to many cases of stream piracy; hence there was rejuvenation without uplift.

The upper strata of the mountains are correlated with the White River formation. This extends considerably the known distribution of the Oligocene series. Study of the formation leads to the conclusion that some of the lower beds were deposited by a river and that most of the rocks were laid down in a lake. The lake was fed by a river flowing northward from the Black Hills and transporting large quantities of calcareous silt from South Dakota to western North Dakota.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Osann, A. "Petrochemische Untersuchungen. Th. I," *Abh. Heidelberger Akad. Wiss., Math.-naturw. Kl.*, 1913. 4to, 163, pls. 8.

In this volume the author attempts to answer two important questions in chemical petrography. First, what are the laws of the chemical composition of igneous rocks, and what are the characteristics separating the rocks of the alkali series from those of the alkali-lime? Second, what are the most important chemical differences between sediments and igneous rocks, and how may these be made of value in determining the origin of crystalline rocks?

To answer these questions, use is made of nearly thirteen hundred chemical analyses. The relationships between the oxides which vary most in their proportions in sediments and igneous rocks and which are also of value in comparing the igneous rocks, have been determined. Molecular proportions are used and recomputed to a constant sum so that they may be diagrammatically compared. Unimportant and accessory constituents are omitted, but TiO_2 and ZrO_2 are added to SiO_2, BaO and SrO to CaO, and MnO to iron, which is calculated as FeO. The four relationships computed are:

1. $SiO_2:Al_2O_3:(Fe, Mg, Ca)O = SAlF$ proportions. In this series the alkalies are entirely omitted. In sedimentary rocks this relationship leads to a grouping in three classes; siliceous, aluminous, and calcareous.

2. $Al_2O_3:CaO:(Na,K)_2O = AlCAlk$ proportions. This shows the more important differences between sediments and igneous rocks, and, in combination with the preceding, the characteristic differences between the alkali and alkali-lime series.

3. $Na_2O:K_2O = NK$ proportions. Recalculated to 10.

4. $MgO:CaO = MC$ proportions. Recalculated to 10.

The last two are of importance in separating igneous rocks from sediments.

The first two may be represented graphically in a triangular diagram after recalculation to 30. The results are plotted to the nearest 0.5. A

recalculation to 100 and representation to the nearest whole number seems simpler to the reviewer, especially if the calculation is performed on a slide-rule.

Pp. 68 to 161 are devoted to nearly 1,300 analyses recomputed to these four values; the chemical values used are taken from Osann's former tables and are referred to by number. In Table I the rocks are arranged according to the decreasing S, increasing Al, and decreasing F values; in Table II according to the AlCAlk values. Table III is arranged under the ordinary rock-names, the SAlF, etc. values being given as well as references to the literature.

Of all the analyses computed, only two coincided in all four relationships, namely, the quartz-monzonite from Elkhorn, Montana, and an average of four analyses of the Butte "granite." Since the two rocks are from the same batholith, the similarity is not surprising.

To follow the discussions of the various relationships, it is necessary to look at the accompanying diagrams. No attempt, therefore, will be made to summarize them here, and the reader is referred to the original paper.

While the present work deals only with the igneous rocks, a number of examples of sedimentaries and crystalline schists are given for comparison. A second part, dealing with sediments and schists is to follow.

This work represents an enormous amount of patient labor. It should be of extremely great value for the visualization of chemical differences in rocks.

OSANN, A. "Über topische Gesteinsparameter," *Sitzb. Heidelberger Akad. Wiss. Math.-naturw. Kl.*, 1914, A 26, pp. 15, pls. 3, fig. 1.

Rocks of a petrographic province, or from a rock-mass showing zonal or other differentiation, or from any igneous body and its satellites, when plotted in a triangular diagram after Osann's well-known system, show clearly their mutual relationships. If it is desired to show the general relationships of any igneous to the average igneous rock, it is only necessary to indicate the latter by a point properly placed. In this paper the mean of Clarke's and Washington's average rocks is taken and is recalculated in the Osann system. This gives a rock not far from the pyroxene-amphibole-biotite-diorite from Electric Peak. The latter, however, has more dioritic characters, the former more monzonitic. To show more clearly the variations of other rocks from this mean, it is shifted to the center of the triangle and the co-ordinates

of the other rocks are recalculated by dividing their A, C, and F values by the same values in the average rock. The new values are indicated by A_t C_t and F_t, and are called "topical" parameters. As recalculated, the plutonic rocks lie equally distributed in each quadrant of the figure.

OSANN, A., and UMHAUER, O. "Über einen Osannithornblendit, ein feldspathfreies Endglied der Alkalireihe von Alter Pedroso," *Sitzb. Heidelberger Akad. Wiss., Math.-naturw. Kl.*, 1914, A 16, pp. 10, pls. 2, bibliography, analyses.

Description of narrow, black dikes occurring in a light-colored alkali-syenite in Portugal. The rock consists entirely of amphibole (osannite) with a little magnetite; light-colored constituents, biotite, and pyroxene are entirely wanting.

PALMER, HAROLD S. "Geological Notes on the Andes of Northwestern Argentina," *Amer. Jour. Sci.*, XXXVIII (1914), 309–30, figs. 9.

This paper gives the results of a reconnaissance trip from Salta, Argentina, to Calama, Chile. The author finds evidence of the deposition of Paleozoic sediments, their later metamorphism during or following the intrusion of granite and granite-porphyry, subsequent erosion, deposition of Jurassic sediments, a period of vertical movements which folded and faulted the rocks, and a period of great volcanic activity, beginning in the Tertiary and continuing till recent times, during which rhyolites and andesites were erupted. There is evidence of some glaciation in the Eastern Cordillera.

PIRSSON, L. V. "The Microscopical Characters of Volcanic Tuffs —A Study for Students," *Amer. Jour. Sci.*, XL (1915), 191–211, figs. 6.

The author points out the difficulty in determining the tuffs when they have become altered by weathering, by burial under later sediments, or by metamorphism, and the difficulty in determining whether such rocks are igneous or sedimentary. No systematic or adequate treatment of the tuffs being given in petrographic textbooks, he tells his own experience in studying them.

Fragmental volcanic material is classified, according to the size of the material, into bombs, lapilli, ashes, and dust. The coarser material

when consolidated produces breccias, the lighter ashes and dust, tuff. The term volcanic conglomerate should be restricted to water-laid conglomerates consisting of volcanic material; volcanic agglomerate to the coarse material filling the upper portions of old volcanic conduits. Volcanic tuffs may consist of glass (vitric tuffs), crystals (crystal tuffs), or fragments of rocks which may be holocrystalline or partly glassy (lithic tuffs).

Under the head "Vitric Tuffs" the formation of tuffs, the forms of the particles, the appearance of a thin section of consolidated tuff, the shapes of the individual dust particles, the texture of the rock and the magmatic relations of the material are considered, while under "Crystal Tuffs" the origin of the crystals, their form, and the interstitial fillings, and under "Lithic Tuffs" the origin, appearance, and character are described. Although these type tuffs may occur, it is more common to find transition rocks. The author concludes his paper with a discussion of the alteration of tuffs, including their weathering and consolidation, devitrification, and metamorphism.

PIRSSON, L. V. "Geology of the Bermuda Island," *Amer. Jour. Sci.*, XXXVIII (1914), 189–206, 331–44, figs. 2, analysis 1.

This is a geologic and petrographic study of material obtained from a bore hole, 1,413 feet deep, in Bermuda. Roughly, the section, beginning at the top, shows chalky Bermuda limestone to 380 feet, sea-level being 135 feet below the surface. Between 380 and 590 feet the hole passed through fragmental volcanic material, greatly altered, soft and claylike with harder inclusions. From 590 to 695 feet the material is sand and gravel composed of water-worn volcanic débris. Beginning at 695 feet there is a series of lava flows, basaltic in character, dense and black to gray, and amygdaloidal at the tops. The separating lines between the flows are at 695, 850, 1,002, 1,080, 1,200, 1,385, and 1,413 feet, the latter the bottom of the well.

From the character of the material overlying the solid lava, the conclusion is drawn that Bermuda was once a volcanic island which was entirely cut away to the level of the sea by wave-action, and subsequently formed the platform for the growth of a coral island.

A petrographic study of the material collected from the well was made difficult by the fact that a churn-drill was used, consequently the material was in a finely divided state. The lava consists of two kinds, both belonging to the alkali series: (*a*) feldspar-free basalts, including

melilite-basalt, and (*b*) extrusives related to monchiquites and lamprophyres. For one of the latter, consisting of small biotites in a cement of analcite, which in sections from farther down is apparently nephelite, the name *bermudite* is suggested.

POWERS, SIDNEY, and LANE, ALFRED C. "Magmatic Differentiation in Effusive Rocks," *Bull. Amer. Inst. Min. Eng.*, 1916, 535–48, figs. 4.

From a series of drill cores taken from the Triassic basalt flows of Cape d'Or, Nova Scotia, the authors have had thin sections and chemical analyses made from material taken at different depths. They found that there is a concentration of the leucocratic, feldspathic constituents at the top of the flow, a slightly greater percentage of augite in the center, and of feldspar near the base. Further, there is a large amount of glass at both top and bottom, but more at the top, a rather uniform quantity of iron ores throughout, and a certain amount of olivine only at the top. The top and bottom of the flow were quickly chilled, and contain almost equal amounts of feldspar and augite. They probably show the original composition of the magma. With respect to the grain, it was found to differ in various places in thick flows. It is coarsest just below the center where the cooling was slowest, and more or less glassy at top and bottom. The specific gravity was found to be greatest just below the center, least at the top, and of intermediate value at the base.

POWERS, SIDNEY. "The Geology of a Portion of Shelburne Co., Southwestern Nova Scotia," *Trans. Nova Scotian Inst. Sci.*, XIII (1915), 289–307, figs. 3.

Granites, quartz-diorites, and aplitic granites, intruded into sediments during Middle Devonian diastrophism, produced extensive contact-metamorphism, staurolite-schist being developed ten miles from the nearest granite outcrop. Two analyses, computed from the rock mode, are given.

QUENSEL, P. D. "Geologisch-petrographische Studien in der patagonischen Cordillera," *Bull. Geol. Inst. Upsala*, XI (1911), 1–114, figs. 27, pls. 4, map 1, bibliography, analyses.

This paper gives the results of a remarkable reconnaissance journey taken along the Patagonian Andes from north to south by Doctors

Skottsberg, Halle, and Quensel, and constitutes the inaugural dissertation of the latter at the University of Upsala. No attempt was made to map the formations in detail, it being thought more desirable to cover a greater area with less accuracy. A great number of rocks are described, both alkali and alkali-lime, and numerous analyses are given. Among the rocks are biotite-monzonite, quartz-monzonite, kentallenite, nordmarkite, quartz-mica-diorite, tonalite, tonalite-porphyry, biotite-granite, bronzite-orthoclase-gabbro, granite-porphyry, quartz-hypersthene-diorite, essexite, essexite-gabbro, quartz-essexite-diabase, comendite-granophyre, hornblende-akerite, essexite-porphyrite, camptonite, trachydolerite, and hypersthene-andesite.

Quensel, P. D. "Die Quarzporphyr- und Porphyroidformation in Südpatagonien und Feuerland," *Bull. Inst. Upsala,* XII (1913), 9–40, figs. 12, analyses.

Quensel, P. D. "The Alkaline Rocks of Almunge," *Bull. Geol. Inst. Upsala*, XII (1914), 129–200, pls. 12, map 1, analyses.

The alkaline rocks of Almunge represent a deep-seated section of the conduit through which magma flowed for some time, as indicated by contact metamorphism of the surrounding rocks. The central mass of umptekite is surrounded by a rim of aplitic material. Within the main body, mostly in the eastern portion, are small areas of nephelite-syenite containing a high percentage (7 to 8 per cent) of lime. This lime does not enter into the feldspar, which is orthoclase and very sodic plagioclase, but is contained in the dark minerals. For this rock the author proposes the name *canadite.*

Rankin, G. A. "The Ternary System $CaO–Al_2O_3–SiO_2$," *Amer. Jour. Sci.*, XXXIX (1915), 1–79, figs. 19. With optical study by Fred. E. Wright.

While numerous papers on the $CaO-Al_2O_3-SiO_2$ system have been published, all of them have been incomplete. This paper contains a summary of work performed, and is the first attempt to determine all of the compounds, both binary and ternary, in this system. The equilibrium diagram representing the stability relations contains 14 fields. A list of the compounds obtained, with their crystal system, crystal habits,

cleavage, hardness, elongations, orientations, refractive indices, optical characters, and axial angles is given. There are also lists giving the compositions, transformation-points, and melting-points.

RICHARDS, H. C. "The Volcanic Rocks of South-Eastern Queensland," *Proc. Roy. Soc. Queensland*, XXVII (1916), 105–204, pls. 11, including one map, and many chemical analyses.

The area here described embraces some 4,000 square miles in south-eastern Queensland. The region was one of considerable igneous activity, the volcanic products being approximately 3,000 feet in thickness and divisible into three well-marked series. The upper division has a maximum thickness of 2,000 feet and is made up of basalt, andesitic basalt, and basalt flows. Some pyroclastic material occurs. The middle division has a maximum thickness of 1,000 feet and is made up of flows and plugs of acid and sub-acid lavas and considerable pyroclastic material. The lower division has a maximum thickness of 1,500 feet, though it averages only 100 feet, and is made up mainly of basic lavas with some andesite. With the exception of the Brisbane tuffs, the age of the flows is Cainozoic. The genetic relationship between the rocks is shown by various diagrams. The author thinks that the alkaline rocks in this region were not formed by the assimilation of limestone, and does not find evidence of the association of sub-alkaline rocks with folded earth movements.

RINNE, F. "Beiträge zur Kenntnis der Kristall-Röntgenogramme," *Ber. math.-phys. Kl. k. sächs. Gesell. Wiss. Leipzig*, LXVII (1915), 303–40, figs. 27, pls. 20.

Describes apparatus used and gives results obtained by the examination by the Röntgen rays of variously oriented crystals.

RINNE, F. "Metamorphosen von Salzen und Silikatgesteinen," *Jahresb. d. Niedersächs. geol. Vereins z. Hannover*, 1914, 252–69.

Shows the effects of hydro-, hydrothermal-, pressure-, and hydrothermal-pressure-metamorphism on salt deposits, and compares the results with those produced in silicate rocks. The causes and the results produced in the salt alterations are broadly the same as those produced in the silicate rocks.

RINNE, F. "Beitrag zur optischen Kenntnis der kolloidalen Kieselsäure," *Neues Jahrb. Min., Geol., u. Pal.*, B.B. XXXIX (1914), 388–414, figs. 12.

Describes apparatus and results obtained by the examination at different temperatures, between $-600°$ and $+1000°$, and by light of different wave lengths, of various amorphous silicates, such as quartz-glass, hyalite, precious opal, moldavite, obsidian, and marekanite. It was found that these substances fell into two groups, water-free or water-poor, and water-rich. In the former the refractive indices progressively increased with temperature changes, while in the latter they increased to the neighborhood of 0° and then decreased.

RINNE, F. "Die Kristallwinkelveränderung verwandter Stoffe beim Wechsel der Temperatur. I," *Centralbl. Min., Geol., u. Pal.*, 1914, 705–18, figs. 9.

With the apparatus described in the preceding paper, the author found that the angle of the rhombohedron (1011) in calcite, dolomite, siderite, and rhodochrosite increased with increasing temperature. Above 0° the curve is a straight line, below 0° it is slightly curved. The plagioclase feldspars show a decrease in the angle 001–010 with increasing temperature. Albite shows the greatest change, anorthite the least. The curves are very flat at low temperatures and rapidly drop at high temperatures.

SCHMIDT, EDUARD. "Die Winkel der kristallographischen Achsen der Plagioklase," *Chemie der Erde*, I (1915), 351–406, figs. 13, bibliography.

A study of the plagioclase feldspars, unusually valuable since the material was analyzed. There are new determinations of the cleavage angle (001):(010), which show that this angle is a linear function of the An. content. The specific gravity determinations, with one exception, agree very well with the determinations made by Day and Allen on artificial feldspars. The value for the labradorite from Labrador is given as $2.689+0.003$, and its composition as An. between 49 and 50; the artificial feldspar Ab_1An_1 gives a value, according to Day and Allen, of 2.679. The material from Labrador, however, was zonal, and the An. percentage as computed from the silica, lime, alkalies, etc., varied between 44.8 and 55.8. It is possible, therefore, that the anorthite

percentage should have been taken higher. There are also new values for the angles between crystallographic *a* and *c* (β) and between *a* and *b* (γ). Query: Is not the anorthite cited as from the Bonin Islands, Japan, from Miyaké-jima instead?

SCHOFIELD, S. J. "The Origin of Granite (Micropegmatite) in the Purcell Sills," *Canada, Dept. Mines, Museum Bull., No. 2, Geol. Series, No. 13*, 1914, pp. 32, figs. 4, pl. 1.

The Purcell sills represent, according to the author, intrusions from a single intercrustal reservoir, which he apparently believes contained the magma already differentiated according to density, the relatively acid portion collected in irregularities and projections of the roof of the chamber and grading downward into more basic materials. Crustal movements produced fissures which tapped the reservoir at various levels, so that acid and basic materials would rise through separate fissures and spread between the overlying strata as sills. The sills themselves are simple or composite. The former solidified in the usual manner of intrusives; the composite sills differentiated in place, some of them having basic upper and lower contacts and an inner portion which is more acid in the upper part and more basic in the lower. The composition of the sills may be slightly modified by assimilated material derived from included fragments or from the inclosing rock.

SCHOFIELD, S. J. "The Pre-Cambrian (Beltian) Rocks of Southeastern British Columbia and Their Correlation," *Canada, Dept. Mines, Museum Bull., No. 2, Geol. Series, No. 16*, 1914, pp. 13, map 1.

SCHWARZ, E. H. L. "The Granite Dykes of the 3,520 Foot Level, Kimberley Mine," *Trans. Geol. Soc. S. Africa*, XVII (1914), 3–23, fig. 1, pls. 4.

SEDERHOLM, J. J. "On Regional Granitization (or Anatexis)," *Congrès géol. intern., Canada*, 1913. Pp. 6.

A study of migmatites and the processes by which granites work their way into adjacent rocks.

SHAND, S. J. "On Veins and Inclusions in the Stellenbosch Granite," *South African Jour. Sci.*, 1913, pp. 5, pls. 3.

Describes various types of veins and inclusions in granite.

SHAND, S. J. "On Saturated and Unsaturated Igneous Rocks," *Geol. Mag.*, X (1913), 508–14.

Saturated, or sated, minerals are those which are capable of forming in the presence of free silica; unsaturated, or unsated, are those which do not appear in association with free silica. Among the former are orthoclase, albite, anorthite, pyroxenes, amphiboles, micas, tourmaline, spessartite, topaz, titanite, magnetite, ilmenite, apatite, zircon; among the latter, leucite, nephelite, sodalite, noselite, analcite, cancrinite, hauynite, melanite, melilite, olivine, pyrope, picotite, corundum, and perovskite.

SKEATS, ERNEST W. "The Occurrence of Nepheline in Phonolite Dykes at Omeo," *Australasian Assoc. Adv. Sci.*, XIII (1912), 126–30, map 1.

Previously reported occurrences of feldspathoids in Victoria are shown to be undemonstrated or inaccurate. Here are described several phonolite dikes from near Omeo. The texture is trachytic, the minerals soda orthoclase, nephelite, and aegirite.

SKEATS, ERNEST W. "The Geology and Petrology of the Macedon District," *Bull. Geol. Surv. Victoria, No. 24.* Melbourne, 1912. Pp. 58, pls. 28, map 1, analyses.

This paper gives a short geologic history of the Macedon District, 40 miles northwest of Melbourne. The principal part of the paper, however, is devoted to the petrology of the region. The rocks described are dacites, granodiorites, granodiorite-porphyries, solvsbergites, trachytes, limburgites, anorthoclase-basalts, basalts, various metamorphic rocks, and two rocks described as macedonite and woodenite. Both are related to orthoclase-basalts and mugearites. The *macedonite* is dense and fine-grained with megascopically visible biotite flakes. The minerals shown microscopically are alkali feldspar, anorthoclase(?), acid plagioclase, biorite, olivine, hornblende, augite, apatite, calcite, chlorite, serpentine, and chrome spinel. The *woodenite* is a dark, dense rock consisting of augite, magnetite, and olivine in a groundmass of dark glass. It agrees closely in chemical composition with absarokite. Twenty-nine analyses are given of the various rocks, and they are recomputed in the C.I.P.W. system. The sequence of the alkali rocks in this district is discussed.

SOBRAL, JOSÉ M. *Contributions to the Geology of the Nordingrå Region.* Upsala, 1913. Pp. 178, pls. 12, map 1, fig. 1, many analyses.

The rocks of the Nordingrå district belong to three different geologic epochs. The oldest is composed entirely of igneous rocks—anorthosites, gabbros, and granites—and is of most importance. The second group consists of Jotnian quartzite and sandstone; the third of more recent diabases and monzonites intruding and covering the sandstone. The topography of the region is due in part to faults, some of the firths and valleys certainly having been caused by dislocations, but the consolidation of the magma and the composition of the igneous rocks have had the greatest effect upon the land forms.

Analyses are recalculated into the C.I.P.W. and Osann systems.

A new dike-rock, consisting essentially of albite and augite with titanite, magnetite, and apatite, is described and analyzed. The author calls it *värnsingite*. An analysis is given.

SOMERS, RANSOM EVARTS. "Geology of the Burro Mountains Copper District, New Mexico," *Bull. 101, Amer. Inst. Min. Eng.*, 1915, 957–96, figs. 25.

This paper deals chiefly with the economic geology of the region, although a few pages are devoted to the general geology and the igneous rocks which occur. Among the latter are granite, quartz-porphyry, quartz-monzonite, and volcanic breccias.

SOMMER, MARTIN. "Beitrag sur petrochemischen Kenntnis des Lausitzer Granitmassivs," *Ber. k. sächs. Gesell. Wiss.*, 1915. Pp. 71, pls. 4, including one map.

The Lausitz granite area to the east of Dresden consists of twelve varieties of granite; a normal granitite, a normal granite, and ten other varieties. All but one of these varieties were analyzed, and these, as well as a number of older analyses, are given. The molecular percentages are computed and the results plotted in Osann's ACF, SAlF, and AlCAlk diagrams and in FeCaM, CaNaK, and M_2O_3 MO M_2O triangles. All of these clearly show the relationships between the various granites, for the points lie practically along straight lines, or within small circles. The relationships between the different rocks are discussed.

Reviews

The Origin and Evolution of Life on the Theory of Action and Interaction of Energy. By Henry Fairfield Osborn. Charles Scribner's Sons. Pp. xxi+322. Large 8vo.

This striking book is an elaboration of a series of lectures given as the Hale Lectures of the National Academy of Sciences, Washington, April, 1916. It is essentially an exposition of the author's "tetrakinetic theory," perhaps the most ambitious and comprehensive causo-mechanical theory of evolution since that of Darwin. Unlike most theories of evolution, which posit life already begun and deal with its subsequent evolution, the present author begins with a consideration of the lifeless world and discusses the physicochemical factors that favored the origin of living matter.

The viewpoint is avowedly dynamic and energistic throughout, and is therefore completely in accord with modern tendencies in biology, which are becoming progressively less morphological and more purely physiological.

The author has called into consultation many leaders in the various branches of science, including physics, physicochemics, immunology, geophysics, geochemics, astronomy, physiography, bacteriology, cytology, genetics, etc. The expert opinion of this competent group has been focused upon the solution of the problems in hand. No important body of knowledge that might bear on the subject is omitted or evaded.

In brief the author's "tetrakinetic theory" of evolution is that all evolutionary changes are the result of the continuous interaction of four energy systems, two of which are intrinsic or within the organism, and two extrinsic or outside of the organism. These four energy systems are:

1. Inorganic environment: the physicochemical energies of space, of the sun, earth, air, and water.

2. Organism: the physicochemical energies of the developing individual in the tissues, cells, protoplasm, and cell-chromatin.

3. Heredity-germ: physicochemical energies of the heredity chromatin, including the reproductive cells and tissues.

4. Life environment: physicochemical energies of other organisms.

The first and fourth factors are what we have usually called the environment and the second and third are what we have called heredity. According to the conventional view each generation of individuals is the result of the co-operation of heredity and environment. There is therefore nothing essentially new about this classification of energy complexes. What is really new is the consideration of these factors in terms of energy.

The inorganic environment is described as so highly adapted for organisms that the non-existence of the latter would be well-nigh inconceivable. In this the author follows closely L. J. Henderson and T. C. Chamberlin. The organism is viewed as a system of parts each affecting the growth of the others through the instrumentality of "chemical messengers" or hormones. It is this interaction of energies that gives organization to the individual and limits its size as a whole and the relative size of its parts. Gradual changes in the activity of one gland may alter quantitatively or qualitatively the chemical messengers produced by it, and progressive changes in one or many structures may result.

The heredity-chromatin of Osborn is evidently much like that of Morgan and his collaborators, with all of its intricate organization and its mechanism for producing new assortments of characters. The treatment of this energy system is a trifle vague and mystical in that it is supposed to go on its evolutionary way in a highly conservative fashion, guided only to a very limited extent by other energy complexes. Its changes are orderly and from generalized to specialized. Once the chromatin becomes specialized it cannot reverse and return to a generalized condition. The slow, orderly, self-contained changes of the heredity-chromatin are supposed to account for the orthogenetic phenomena so common in paleontological materials.

The "life environment" is, in a sense, a restatement in energy terms of Darwin's idea of the struggle for supremacy and survival of the fittest, but the struggle is inter- rather than intra-specific. Every environmental complex is a battleground on which the various groups that have become specialized for that particular complex struggle for space to multiply. One group may perfect an offensive equipment, another a defensive armament. Either type may go to extremes of specialization, so that a radical change of environment may find them nonplastic and irreversible. This is the author's explanation of many unaccountable extinctions.

Part II of the book is an application of the principles discussed in Part I to the evolution of the various animal groups. It must suffice

here merely to give the titles of the chapters: chap. iv, "The Origins of Animal Life and Evolution of the Invertebrates"; chap. v, "Visible and Invisible Evolution of the Vertebrates"; chap. vi, "Evolution of Body Form in the Fishes and Amphibia"; chap. vii, "Form Evolution of the Reptiles and Birds"; chap. viii, "Evolution of the Mammals."

The author is consistent throughout in viewing the organism as an energy complex. A great carnivorous Tyrannosaurus, for example, is chosen as a culmination of the offensive type of energy complex, while the horned herbivorous dinosaurs, known as Ceratopsia, are viewed as a defensive energy complex. The evolution of these two highly specialized complexes is an example of the "counteracting evolution" of offensive and defensive adaptations.

The book is so full of meat that the reviewer finds himself at a loss to do it justice in a limited space. So many stimulating suggestions are made in every chapter, indeed on almost every page, that one must read it carefully to get its full import. While there are many points that invite controversy, it must be borne in mind that the evident intention of the author is merely to establish a new threshold for departure, not to make an exhaustive explanation of evolutionary phenomena. The way toward future research in many lines is pointed out and a constructive plan for future work is outlined. This in itself is a contribution of the highest importance, since it places a new milestone beside that long and ancient highway of "the evolution of the evolution idea."

H. H. N.

Organic Evolution, a Text-Book. By Richard Swann Lull. New York: Macmillan, 1917.

This compact volume of seven hundred and twenty-six pages and nearly three hundred figures, by the distinguished professor of vertebrate paleontology of Yale University, is one of the most satisfactory texts on organic evolution known to the writer. Especially satisfactory is it from the side of paleontology, and paleontology is and must remain the clearing house of all evolutional theories and doctrines. It treats of the history of the evolutional doctrine; the accepted and disputed factors of organic evolution; and the evidences of evolution, drawn from living and fossil organisms, including the origin of vertebrate life and of its chief groups; the adaptation, especially of vertebrates, to terrestrial, cursorial, volant, aquatic, desert, and cave life; the evolution of some of the best known types of mammals, the horses, elephants, camels, and,

in the final chapter, of the evolution of man himself. Nor does this brief summary of the contents of the volume include instructive chapters on the physical basis of life, classification of organisms, the geological, geographical, and bathymetrical distribution of organisms, and on the extinct dinosaurs in particular.

Few available sources of information have been overlooked, and in an attentive reading of the book the reviewer has found very few misstatements of facts. Various disputed theories of the origin of organisms or their functions are discussed, but the author, commendably, has not ventured many himself.

In a few words the work is an excellent summary of the theories, facts, and factors of evolution, adapted especially to the needs of the student and presented in a readable way. The geologist as well as the biologist will find it of interest.

S. W. W.

Geology and Geography of the Galena and Elizabeth Quadrangles. By A. C. Trowbridge and E. W. Shaw, with chapter on the "History of Development of Jo Daviess County," by B. H. Schockel. Illinois State Geol. Survey, Bull. 26, 1916. Pp. 233, pls. 25, figs. 50.

The district lies in the extreme northwest corner of Illinois, almost entirely within the Driftless Area. The lead and zinc deposits having been described in previous reports, the present writers discuss the general geology of the region and the processes which have produced its topographic features.

The Platteville limestone, Galena dolomite, Maquoketa shale, and Niagara limestone outcrop within the quadrangles; deep wells have penetrated the Potsdam, Prairie du Chien (=Lower Magnesian) and St. Peter formations. The Quaternary deposits include fluvio-glacial terrace materials, more or less isolated areas of loess, a small area of Illinoian (?) drift, and recent valley alluvium.

The work of wind, ground water, and stream erosion are discussed at length. The origin of two surface levels above the present valleys is considered, and though the evidence collected here is not decisive proof of peneplain origin, data from adjoining districts warrants the acceptance of that hypothesis. The age of these surfaces is uncertain. Following Salisbury, the writers suggest that the Niagara flat is of Pliocene age and the Galena flat earliest Pleistocene.

In chap. x, on the history of development of Jo Daviess County, the lead-zinc mining industry is recognized as the cause of the early settlement and development of the region. The rough topography and relatively thin and infertile soils of the Driftless Area make agriculture less profitable here than in the surrounding glaciated country.

H. R. B.

Geology of the Navajo Country. A Reconnaissance of Parts of Arizona, New Mexico, and Utah. By HERBERT E. GREGORY. U.S. Geological Survey, Professional Paper No. 93. 4to, pp. 161; maps.

This useful and valuable summary of Professor Gregory's long studies of the Navajo country covers an area of more than twenty thousand square miles, a region inhabited almost exclusively by the Navajo, Hopi, and San Juan Indians. The report deals fully with the geography, stratigraphy, igneous rocks, structure, physiography, and economic geology of this little-known region, and is illustrated with numerous photographs and two pocket maps of the geography and geology.

The sedimentary rocks, from the Pennsylvanian to the Eocene, with part of which at least the reviewer has some acquaintance, are treated extensively in their various subdivisions. The descriptions and illustrations will serve as an excellent guide to the future explorer. Their correlation is in part one of peculiar difficulty because of the absence of characteristic fossils. Permian strata are identified with doubt. No fossil vertebrates have hitherto been discovered in this region, but the reviewer confidently believes that they will be in future, probably in the lower part of the Moenkopi and underlying formations. The strata referred to the De Chelly formation are certainly higher than the fossiliferous Permian beds farther east, and might with equal propriety be called Lower Triassic. The Shinarump conglomerate, lying below Upper Triassic strata, as determined by their vertebrate fossils, is not only widespread throughout this region, but is identified with assurance by the present writer as far north as the Wind River Range in western Wyoming. It seems everywhere to be a reliable guide to the fossiliferous Triassic beds immediately above it. The fossil-bearing Chinle beds of the Upper Triassic are doubtless equivalent in age to those called by the writer the Popo Agie beds some years ago. Their description is characteristic.

So also the Jurassic is recognized with doubt in the Navajo, Toldito, and Wingate sandstones of from four hundred to fifteen hundred feet in total thickness. Doubtless they include the equivalent of the Baptanodon beds of Wyoming, which in the southern part of that state are also represented by massive sandstones. But just how much of these sandstones will prove to be of Jurassic age is doubtful. The McElmo, which farther east may be represented by dark-colored shales, is also doubtfully located in the Jurassic. It probably includes the equivalent of the Morrison beds, which from the north to the south become progressively more sandstone, and should, the writer thinks, be included in the Comanche or Lower Cretaceous.

The more precise correlation of the Mesaverde and Mancos beds with the Colorado and Montana groups of the Cretaceous ought not to be a matter of difficulty. The writer, from his observations in the Gallina Mountain region, just east of the San Juan Wasatch beds, believes that he identified both the Benton and Niobrara from characteristic fossils. It is much to be desired that local geological names should be abandoned wherever possible. For instance, the Eagle Ford and Austin shales of Texas are positively and precisely correlated with the Benton and Niobrara of Kansas by their vertebrate fossils, and their names should be abandoned.

The limited outcrops of Tertiary rocks in the Chuska Mountains and farther to the southwest are referred with doubt to the Eocene, because of the absence of fossils.

Altogether Professor Gregory's work in these fields will serve as an excellent guide to the future explorer. Much remains to be done in the more precise correlation of the strata; and the prospects for the vertebrate paleontologist, at least, are full of encouragement; he has been groping hitherto.

S. W. W.

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CORAL REEFS AND SUBMARINE BANKS

W. M. DAVIS
Cambridge, Massachusetts

PART II

Fundamental postulates of the glacial-control theory.—If we now return to the consideration of the principal postulate of the glacial-control theory, it should be noted that the features appealed to in evidence of long-enduring ocean-bottom stability are not directly concerned with the deep ocean floor itself, for the ocean floor is inaccessible to geological observation; nor do they concern the geological structure of islands with elevated reefs which give a decipherable record, for nearly all of these islands seem to have had elevations and subsidences during their long history. The glacial-control theory is chiefly concerned with atolls and submarine banks, the history of which is not directly decipherable; and the features which are taken to demand long-enduring crustal stability are, as already noted, the nearly level floors and the similar and moderate depths of atoll and barrier-reef lagoons and of submarine banks, although they are all covered with unconsolidated calcareous deposits of recent deposition and unknown thickness.

In seeking to account for these well-substantiated submarine features, the glacial-control theory advances reasons for thinking that the nearly level lagoon deposits must be of small thickness and

must therefore rest on nearly level rock platforms at a moderate and fairly uniform depth in all the coral seas. It is next argued that the production of the inferred rock platforms was preceded by subaërial erosion and marine abrasion during a long preglacial period of "general crustal stability in the coral sea," whereby lofty volcanic islands were worn down to insular lowlands. Then, in view of the plausible inference that reef-making corals were killed during the glacial period, it is further supposed, as previously outlined, that the chilled and lowered ocean was free to cut away the dead reefs and to reduce the worn-down islands to flat platforms. Finally, as the ocean rose and warmed in postglacial time, the existing reefs are believed to have grown up around the platform margins, while unconsolidated calcareous deposits were strewn evenly over the platform surface; or, if reefs did not grow up, the platforms remained as submarine banks.

The ingenuity with which the successive conditions and processes are enchained is certainly admirable, but the fundamental assumptions do not seem to be fully established, and the conclusions reached are not unescapable. The links of the chain of argument must be separately examined. The plausible inference that reef-making corals were killed during the glacial period will be considered in the next two sections.

Coral reefs not destroyed during the glacial period.—It is certainly plausible to suppose that reef-building corals may have been killed by the lowering of oceanic temperatures during the glacial epochs of the glacial period, but no sufficient tests of the correctness of this supposition have been brought forward. As far as I have been able to analyze the question, the reefs were not so completely divested of protecting organisms, except along the margin of the coral zone, as to expose them and their inclosed islands to abrasion, for the consequences of such abrasion are not found in the expectable form of spur-end cliffs (*KN*, Fig. 3*b*) on the central islands of fringing or of close-set barrier reefs, as I have elsewhere pointed out;[1] hence this essential element of the glacial-control theory lacks

[1] "A Shaler Memorial Study of Coral Reefs," *Amer. Jour. Sci.*, XL (1915), 223–71; see pp. 236–46. "Problems Associated with the Study of Coral Reefs," *Sci. Monthly*, II (1916), 559–77.

support. The previously stated arguments which lead to this conclusion need not be repeated here, but additional evidence to the same end may be presented from Hawaii, Tahiti, and Murea.

Evidence from Hawaii, Tahiti, and Murea.—Let it first be noted that Hawaii, Tahiti, and Murea are three of four islands—the other is Rotuma, north of Fiji—which Daly instances as having "submarine benches so narrow as to prove the extraordinary power of fresh lavas to resist the Pleistocene breakers" (182). Rotuma I have not seen, but Gardiner's account of it[1] suggests that the narrowness or absence of an abraded bench around it may be due rather to the recency of its latest lava flows than to their resistance. Hawaii also was not reached during my voyage of 1914, but Branner's account of it[2] and the several excellent topographic sheets recently published by the United States Geological Survey of its northern and northeastern coast give good reason for thinking that the general absence of a cliff-backed bench around its shores is due to the recency of the eruptions that have covered most of its slopes with lava flows in which valleys are not yet eroded; while the occurrence of deep consequent valleys and strongly clift intervalley spur ends in the Hamakua district of the northeast coast gives equally good reason for regarding that part of the island as much older than the rest—old enough in fact to have suffered submature dissection and mature abrasion, but at a time when the island stood several hundred feet higher than now, as Branner has so well shown. By constructing longitudinal sections and cross-sections of the great valleys from the topographical maps, I have inferred that the amount of submergence since the valleys were cut down and the cliffs were cut back is some 800 feet. But whether submerged or not, the island of Hawaii ought not to be instanced in proof of the belief that the absence of spur-end cliffs on the central islands of barrier reefs elsewhere in the Pacific is due to the resistance of their lavas: to my reading Hawaii supports the other side of the

[1] J. S. Gardiner, "The Coral Reefs of Funafuti, Rotuma, and Fiji . . . . ," *Proc. Cambr. Phil. Soc.*, IX (1898), 417–503.

[2] J. C. Branner, "Notes on the Geology of the Hawaiian Islands," *Amer. Jour. Sci.*, XVI (1903), 301–16.

discussion, namely, that volcanic islands which are indented by drowned-valley embayments half a mile or a mile wide must, like northeastern Hawaii, have had strong cliffs cut in their spur ends if they were exposed to abrasion during the considerable period required for the erosion of the now drowned valleys; and as such cliffs are prevailingly absent on reef-encircled islands the islands must have been protected from abrasion—that is, their reefs must have been clothed with growing organisms of some sort—while the now drowned valleys were eroded.

Tahiti gives even stronger evidence to the same end. This island consists of a larger and a smaller volcanic cone, joined in an isthmus. The slopes of the cones are submaturely or maturely dissected by deep, steep-sided, radial valleys, the lower ends of which have been embayed by submergence after they were eroded; but the embayments are now, with few exceptions, filled with deltas which have expanded outside of their embayments so as to form a continuous alluvial belt around much of the shore line; it was this "broad belt of low land at the foot of the mountains" which Darwin properly interpreted as indicating "a long stationary period" for Tahiti. It is, however, not the radial valleys but the spur-end cliffs that are the most significant feature of Tahiti in the present connection. Agassiz gave a good account of them. Some of the cliffs rise 500 or 1,000 feet above present sea-level on the more exposed coasts; but the northwestern or leeward corner of the island is without visible cliffs for a short distance. Their origin must have been contemporaneous with the erosion of the valleys; hence the base of the cliffs and the platform that must have been abraded at a small depth below sea-level when the cliffs were cut back must be now, like the distal portion of the valleys, submerged. The depth of submergence, inferred from the cross-section of some of the larger valleys, may well be 500 or 600 feet; the lagoon, much aggraded, is naturally of less depth.

It is immaterial for the moment whether the opportunity for cliff-cutting around Tahiti was given while the ocean was chilled and lowered in the glacial period, or whether it was given while the island stood higher and was, like Reunion, reefless because a sheet of shore detritus prevented coral growth, as I believe is the more

probable explanation.[1] The lesson to be learned here is that the time which sufficed for the erosion of the steep-sided valleys of Tahiti sufficed also for the cutting of its great cliffs; hence, far from proving the power of fresh lavas to resist the breakers, Tahiti proves that, resistant as its lavas may be—and they certainly look very resistant where ledges are exposed in the cliff faces and on the valley sides—the waves of the trade-wind sea can strongly abrade the coastal slope of a volcanic island in the same period of time that is needed for the erosion of submature or mature valleys; and that the spur-end cliffs thus formed may be of such height that they will still rise hundreds of feet above sea-level after the cliff base and the platform in front of it and the valley ends between the clift spur ends are submerged hundreds of feet below sea-level. It therefore still seems to me reasonable to be guided by the conclusion elsewhere set forth that the general absence of spur-end cliffs in the central islands of close-set barrier reefs and especially in islands like Rarotonga, that have only a fringing reef, contradicts the assumption that reef-building corals were killed and that the islands that they normally protect were exposed to abrasion during the glacial period.

In order to avoid misunderstanding, let it be added that many spur ends of reef-encircled islands are nipped off in low, freshly cut bluffs, 5 to 30 feet in height, and that these low bluffs are fronted by wave-swept rock platforms of small breadth visible at low tide; hence these bluffs and platforms must be ascribed to wave work of the lagoon waters now or recently in progress at present sea-level. Further, let it be noted in passing that the subsidence inferred for Hawaii must have taken place while its gigantic young cones were in process of formation by eruption; and that a subsidence of Tahiti during its eruptive growth is also suggested, but less definitely, by its association with its more submerged neighbors. These two instances deserve consideration as antidotes to the prevailing idea that volcanic eruption is necessarily associated with upheaval. It is eminently possible, if not probable, that the reverse relation may often obtain, and still more possible that subsidence may set in shortly after eruption ceases.

[1] "Clift Islands in the Coral Seas," *Proc. Nat. Acad. Sci.*, II (1916), 284–88.

Murea, near Tahiti, may be briefly considered. Its dissection is far more advanced than that of Tahiti; its slopes are less steep, its embayments are much larger and wider; several spur ends of its northwest or leeward coast are rather strongly truncated in sloping facets resembling mature cliffs, but around most of its circuit the spurs descend gradually to sea-level; the barrier reef here is comparatively close-set. Surely, if the great cliffs of Tahiti were cut under the conditions assumed in the glacial-control theory, great cliffs should have been cut at the same time around Murea, especially on its southern and eastern sides; the absence of such cliffs indicates that the sea has not had access to the island shore, or, in other words, that the encircling reef of Murea has long protected the island from abrasion. The absence of cliffs cannot be explained under the glacial-control theory by postulating an exceptional resistance for the lavas of Murea; for if the total duration of lowered sea-level during the glacial period were long enough for small streams to deepen their valleys and for the slow processes of weathering to widen the deepened valleys to the form now seen in the drowned-valley embayments in spite of the exceptional resistance postulated for the island lavas, then the waves of the lowered sea working through the same duration of time should all the more have cut great spur-end cliffs; for there can be no question that the waves of the trade-wind sea are much more powerful agents of island sculpture than the streams of short valleys and the weather changes on the valley sides. The same statement may be made for Rarotonga in the Cook group; it is elaborately dissected by wide valleys, but its embayments are replaced by alluvial plains. Its spur ends are not clift.

The Society Islands, therefore, do not support—indeed, they strongly contradict—the consequences expectable from the glacial-control theory as to the abrasion of preglacial reefs; and I believe that they likewise give no support to, if they do not contradict, the fundamental postulate of the "long period of nearly perfect stability for the general ocean floor" on which that theory is constructed; for the depth of submergence indicated by the form of the mountain slopes that inclose the embayed valleys of these islands demands a greater submergence than the glacial-control theory provides.

Furthermore, the zoölogical evidence provided by Crampton's recent elaborate investigations is so strongly confirmatory of the subsidence which earlier investigators had inferred from similar but briefer studies that the postulate of stability for these islands in particular needs revision. Crampton's conclusion is: "The occurrence of related forms [of land snails] in Tahiti, Raiatea, and Moorea means that in former times these islands were connected by land; that the common ancestral stock ranged over the whole land mass, and that its local products differentiated into the distinct species after the process of subsidence had isolated the mountains now forming the separate islands."[1]

No truncated volcanoes are known in the coral seas.—If atolls have been formed by the processes of the glacial-control theory, then after an atoll is sufficiently uplifted and dissected an abraded volcanic platform, around the margin of which the atoll reef was built up, should become visible. Most uplifted atolls are either not raised enough or not eroded enough to reveal a foundation 40 fathoms or 240 feet beneath their reef level. In eastern Fiji, however, a number of limestone islands, that I believe were formed as atolls, have been sufficiently uplifted and dissected to reveal their volcanic platform if it ever existed. In no case is it laid bare; hence, as far as these examples go they discountenance the theory. I have given details of these islands, taken chiefly from reports by Gardiner and Agassiz, in another paper.[2] There are, on the other hand, a number of uplifted fringing and barrier reefs in Fiji, and also I believe in the New Hebrides, the Solomon Islands, the Philippines, and elsewhere, which rest, as above noted, unconformably on the previously eroded slopes of volcanic or other foundations, and in which the length of the eroded slope is so great—and I believe it may be added, the volume of erosion accomplished in shaping the slope is so large—that neither the length of the slope nor the volume of the erosion can be reasonably explained as the work of subaërial destructive processes while the sea-level was lowered only 40

[1] H. E. Crampton, "Studies in the Variation, Distribution, and Evolution of the Genus *Partula* . . . . ," *Carnegie Institution of Washington*, 1916, p. 296.

[2] "The Structure of High-Standing Atolls," *Proc. Nat. Acad. Sci.*, III (1917), 473–79.

fathoms in the glacial epochs. All such reefs appear to me to demand subsidence for their explanation; but as they all occur in the Western Pacific, and not in the central area where only atolls prevail, they do not bear directly on the atoll problem. All that can be said of such unconformable reefs and of the uplifted and dissected atolls of Fiji is that their evidence is highly favorable to Darwin's theory, and that it is in some degree irrelevant to the origin of open-ocean atolls, which are the main subject of the glacial-control theory.

As far as my reading goes only three sections have been published in which the foundation of an actual coral reef is represented as a truncated volcanic mass. One section is of the island of Mango, Fiji, as interpreted by E. C. Andrews;[1] the truncated surface is represented as covered by a now elevated coral reef into and over which later volcanic rocks are erupted; the section is reproduced as if authentic in de Margerie's translation[2] of Suess's *Antlitz der Ende;* but, as the surface of truncation is drawn below present sea-level and as the accompanying text gives no sufficient evidence of its existence, it must be regarded as hypothetical. My brief visit to the island did not enable me to examine its structure closely; but nothing that I saw gave any support to the theory of its having suffered truncation before its elevated reef was formed, nor did it appear to me that the elevated reef is older than the volcanic rocks that are associated with it. If the island really has been completely truncated, it constitutes a remarkable exception to the rule prevailing in Fiji, where the other volcanic islands have not been cut back enough to form strong shore cliffs.

A second section of a truncated volcanic island is to be found in Pirsson's account of the recent boring at Bermuda,[3] where volcanic rocks were reached at a depth of 245 feet below sea-level and penetrated to a depth of 1,278 feet. It appears to me regrettable that a single boring of this kind should be accepted as giving sufficient

[1] E. C. Andrews, "The General Geology of the Fiji Islands . . . . ," *Bull. Mus. Comp. Zoöl.*, XXXVIII (1900), 1–50.

[2] *La Face de la Terre*, III (1913), 1061.

[3] L. V. Pirsson, "Geology of Bermuda Island; the Igneous Platform," *Amer. Jour. Sci.*, XXXVIII (1914), 189–206.

ground for drawing the volcanic cone with a broadly truncated surface "cut away by the action of the sea" at the depth where igneous rocks were first encountered; almost any other form would accord as well with the recorded facts; indeed, in view of the strong variations of magnetic force on the island surface,[1] it is eminently probable that the buried volcanic surface is uneven; if so, it is also probable that the depth of 245 feet is not the minimum depth of the volcanic foundation; for if the surface is uneven it is not likely that a single boring, located without any knowledge of the understructure, would reach the culminating point.

The third example of a truncated volcanic island is Mangaia in the Cook group, which is briefly described by Marshall as having "a well-developed marine erosion surface forming the summit of the island 650 feet above sea level. An alluvial flat . . . . separates the high volcanic land from a ring of coral 125 feet above sea level . . . . 200 or 300 yards from the volcanic land."[2] This example, being visible, is better attested than the other two. It would seem to represent a volcanic cone that was completely truncated by abrasion before any reef defended it, and then elevated; but the barrier-reef ring now surrounding it may well have been formed during a later depression before a later elevation.

It is not without careful consideration that I have been constrained to reject the assumption that reef-building organisms were so completely killed during the glacial period as to leave the reefs an easy prey to the waves. The assumption is, as already noted, certainly a plausible one at first hearing, and it merits careful examination; but as the result of the best examination that I have been able to devise it proves to be erroneous. Thus a problem is laid before zoölogists: If coral reefs are today limited by temperature conditions and if the ocean were significantly cooled during the glacial period, why were not the reef-building organisms then killed? Perhaps the organisms were killed and the reefs were cut away on islands near the borders of the coral zone, as will be

[1] J. F. Cole, "Magnetic Declination and Latitude in the Bermudas," *Terrestr. Magnetism*, XIII (1908), 49–56.

[2] P. Marshall, "Coral Reefs of the Cook and Society Islands," *Proc. Austral. Assoc. Adv. Sci.*, XIII, 1912, 140–45.

further considered later. Perhaps the corals were very generally killed, but the nullipores were not; if so, the nullipores, although unable to construct a reef alone, might cover and protect the exposed flanks of an already constructed reef for a geologically brief epoch until the corals could again establish themselves upon it.

The floors of atoll lagoons.—Whatever solution the question of the survival of reef-building corals during the glacial period may eventually receive, it may be set aside for the present and return may be made to the main facts upon which the glacial-control theory is built, with the question, Is it really impossible to explain the smoothness of atoll-lagoon floors and of submarine banks without prolonged abrasion of still-standing islands? This seems to me no impossibility. Those smooth surfaces are not the result of abrasion, even if an abraded surface exists beneath them; they are the result of the even distribution of organic sediments by agencies now in operation, whatever the shape of the foundation that the sediments rest upon, as will appear from the following consideration.

As to atolls, it is true that the waters of their lagoons are generally placid, but it is also true that at times of storm they are agitated sufficiently to become turbid by stirring up the bottom sediments. Gardiner's testimony on this point, based on observations in the Maldives, is important:

> It is only in a few protected situations, where the depth is as great as 40 fathoms or more, that the lagoon bottom appears not to be churned up by the currents and waves. In heavy weather the lagoon water is almost milky, and floating surface nets [for zoölogical collecting?] are almost useless on account of the enormous amount of mud in suspension. The total amount of mud that passes out of the lagoon in the water is enormous.[1]

Hence I cannot accept Daly's statements that "the lagoon floor . . . . is little or not at all disturbed by any waves or currents generated in the lagoon itself," and that "the filling and smoothing out of the hypothetical 'moat'" about a subsiding island is little aided by the mud from the reef. "The coarser detritus" washed in from the reef flat often does "form a well-defined terrace slowly

[1] J. S. Gardiner, "The Origin of Coral Reefs . . . . ," *Amer. Jour. Sci.*, XVI (1903), 203–13; see p. 210.

growing inward from the reef," as may be seen in many lagoons, for example, those of Tahiti and Raiatea in the Society Islands. Furthermore, as a large quantity of muddy sediment is formed on the reef flat by disintegrating agencies, organic and inorganic, acting on the blocks and scraps of coral rock washed in from the exterior reef face, and as the interior terrace of white granular detritus is free from fine silt, it follows that an important share of fine detritus from the reef must reach the lagoon floor; and this reef silt, as well as the fine organic sediments formed on the lagoon floor or in the lagoon waters, is distributed by the waves and currents therein generated, as Gardiner states.

Darwin had earlier reached a fair understanding of this problem: "The greater part of the bottom in most lagoons is formed of sediments; large spaces have exactly the same depth, or the depth varies so insensibly that it is evident that no other means, excepting aqueous deposition, could have levelled the surface so equally" (26). In my own limited experience I saw the waters of two barrier-reef lagoons rolling in heavy waves under strong winds—once in Fiji, once in the broad lagoon of the Great Barrier reef off the Queensland coast—and on both occasions the water was gray with suspended sediments. It seems evident that under such conditions the finer sediments of lagoon floors will be lifted chiefly from the shallower parts and will settle in about the same amount everywhere; and the continuation of such changes will tend to produce and maintain a fairly smooth surface of sedimentation, such as actually exists.

Another view has been announced. After assigning a small value to the general distribution of lagoon sediments by the waves of gales and storms, and a large value to the distribution of sediments by currents driven under steady winds, Daly has recently reached the conclusion that lagoon floors thus aggraded during subsidence should not be level, but should be deeper to windward and shallower to leeward; then, on examining charts of atolls and verifying the general levelness of lagoon floors, he concludes that subsidence has not taken place, but that the reefs have grown up and the lagoons have been evenly aggraded in postglacial time because their sediments have been deposited on smoothly abraded

still-standing platforms.[1] The conclusion does not seem tenable because the smooth floors of a good number of medium-sized atoll lagoons in the trade-wind belts have moderate depths, such as 20 or 25 fathoms, and must therefore, even under the glacial-control theory, have been aggraded by 15 or 20 fathoms if their abraded platform lies at a depth of 40 fathoms. Moreover, the fact, more fully stated in the next section, that small atolls have on the average shallower lagoons than large atolls proves that a good share of their sediments is washed in from their inclosing reefs. If aggradation by material thus partly supplied from the margin, partly from locally formed organic detritus, and distributed by trade-wind currents in the lagoons ought to produce a slanting surface of deposition, these lagoon floors should not be level; their levelness therefore contradicts the supposed necessity of slanting aggradation and confirms the theory of equable distribution and even aggradation by the lagoon waters. Hence it may be concluded that lagoon floors tend to become and to remain nearly level, whatever form the foundation of their inclosing reefs may have had, and whatever the thickness of their sediments may be; and, conversely, that the form of a lagoon floor gives no indication of the form of its buried foundation. I am therefore constrained to think that the general levelness of atoll-lagoon floors is no sufficient reason for the existence of a level rock platform at a moderate depth beneath.

The depth of lagoon floors.—If, then, the smoothness of lagoon floors is no sufficient proof of the existence of a smoothly abraded rock floor beneath them, we may next inquire as to evidence for the existence of such a rock floor that is found in the similar depth of atoll lagoons and of submarine banks. The depths are not all alike. As to atolls, Daly has shown that on the average the smaller ones are the shallower, and from this he draws the acceptable conclusion that "the smaller the platform the higher was the proportion of reef débris in the veneer, and the more rapidly has the lagoon area been shallowed" (183), and again that "the filling of the lagoon [by inwashed sediments] is in indirect proportion to

[1] R. A. Daly, "A New Test of the Subsidence Theory of Coral Reefs," *Proc. Nat. Acad. Sci.*, II (1916), 664–70.

the width of the platform [atoll]" (192);[1] but as this conclusion would follow equally well whether the reefs have grown up with the rising ocean around a still standing abraded platform, or in a stationary ocean around a sinking and submountainous foundation, no ground for choice between the two theories under discussion is here provided.

A closer scrutiny of the figures, however, reveals considerable differences of lagoon depth in atolls of about the same size, and this seems more consistent with the variable conditions offered by the theory of intermittent subsidence than with the strictly uniform conditions assumed under the theory of glacial control. For example, among 12 atolls listed in Daly's table as from 21 to 30 kilometers in diameter, the smallest value of maximum lagoon depth is little more than half the value of the largest maximum; and this smallest maximum is in an atoll the diameter of which is greater than the one which has the largest maximum. Ringgold atoll, in Fiji, is given as having a maximum lagoon depth that is more than twice as great as the maximum depth in North Argo atoll, of the same group, though both have the same moderate diameter of 10 miles. Among wide barrier reefs the one adjoining New Caledonia on the northeast has a maximum depth less than half that of the lagoon of similar breadth on the northwest of Viti Levu, in Fiji. Moreover, some lagoons reach unusual depths. In the large lagoon, just mentioned, northwest of Viti Levu, the largest island of the Fiji group, the lagoon deepens and the inclosing reef is submerged, as the distance from the island increases, in such a way as strongly to suggest recent tilting; a sounding of 59 fathoms is the maximum there recorded, but the outermost part of the lagoon has not been measured. The large lagoon of the Exploring Isles in the eastern part of Fiji deepens eastward to 80 or 90 fathoms, and this again suggests tilting, as Agassiz noted. Cases of this kind are as significant as they are exceptional. But it should be noted that many atolls of the Central Pacific are, according to the latest charts of all sources available in the Hydrographic Office at Washington, incompletely surveyed; further exploration is needed

[1] The misprint "direct" in the original article is here changed to "indirect" with the author's approval.

before their testimony can be used. In any case, even in atolls of similar diameter, the depths of the lagoons vary so much that they alone cannot be taken as proving that the atoll reefs have been built up with the rise of the ocean from stationary platforms of uniform depth.

The fact that the maximum depth of atoll lagoons seldom exceeds 40 fathoms does, however, suggest the existence of some control that has prevented the occurrence of greater depths; but this control may be found elsewhere than in the abrasion of platforms at a uniform depth below sea-level. For example, if the subsidence of an atoll or a barrier-reef island is relatively rapid, the reef will be somewhat submerged, the inwash of detritus from the reef will be active, and the increase of lagoon depth will be retarded; if subsidence is, on the other hand, relatively slow, the reef will be maintained at sea-level and will broaden its surface, sand islands will be formed along its edge, and inwash of detritus into the lagoon will practically cease; hence, in spite of slow subsidence the lagoon will not be rapidly shoaled. Thus, unless subsidence be unusually rapid, there appears to be a series of spontaneous reactions which tend to prevent lagoon depths from varying by large measures. Wherever unusually rapid subsidence occurs, the atoll would be drowned and converted into a submarine bank. The scarcity of such banks in the Pacific, as far as it is now explored, suggests very strongly that subsidence has rarely been unusually rapid; and slow, equable, or intermittent subsidence, being a near approach to long-continued stability, does not appear to be particularly incredible. But, however that may be, the known depths of atoll lagoons can be explained as well by the theory of intermittent subsidence as by the glacial-control theory. The depth of submarine banks will be discussed in a later section.

The volume of existing reefs.—The glacial-control theory suggests that a very uniform upgrowth of reefs should take place in the uniformly rising postglacial ocean, and that all existing reefs should therefore be of similar surface breadth and of similar volume. Daly finds this to be the case; he says that "the widths as well as the heights of the existing barrier and atoll reefs are of the proper

size, if these calcareous rims originated on the platforms in post-glacial time" (219). As to the height of reefs we know little, because the depth of their base is undetermined. Nothing is gained by assuming their base to be 40 or 50 fathoms below present sea-level, for the resulting uniformity of height has no verification. However that may be, the visible differences in the height of reefs above their lagoon floors and the breadth of reefs at sea-level seem to me too great to support the above conclusion. Yap, in the western part of the Caroline group, Western Pacific, and Rodriguez, in the Southern Indian Ocean, have broad reef plains, a mile or more in width, attached to the central islands; that of Rodriguez is 4 miles wide on the southwest side of the island. Borabora, in the Society Islands, has a barrier reef and reef flat half a mile or a mile wide, and a comparatively shallow lagoon; Mbengha, in Fiji, has a reef and reef flat of similar width around the southern side of its lagoon; the reef around Nairai, in central Fiji, is a half or a quarter of a mile wide; Budd reef, in northeastern Fiji, is narrow, generally less than a quarter-mile across, and its lagoon is 46 fathoms deep; yet near by is the long and irregular Ringgold atoll, in which the reef is half a mile or a mile wide, though the lagoon is of similar depth to that of Budd reef; Tahiti has a narrower reef, often discontinuous; Fauro, in the Solomon Islands, is fringed with a narrow sea-level reef and surrounded by a submerged bank, 70 fathoms deep in places, on which a very imperfect reef rim is found; Palawan, the southernmost member of the Philippines, is elaborately embayed along its western coast, where the headlands are neither clift nor fringed with sea-level reefs, but are fronted by a broad submerged platform, varying in depth along its length with maximum of 60 fathoms. The Marquesas Islands, nearer the equator than the numerous Paumotu atolls, have no sea-level reefs; their headlands are strongly clift, and a submerged bank extends around them. Various submarine banks have well-defined reef rims that fail to reach the surface, or that rise very discontinuously to the surface, as will be specified below; and some submarine banks are flat and rimless. Differences of these kinds in reef volume are more consistent with the unlike conditions introduced by intermittent subsidence, varying as to rate, amount, place, and

date, than with the uniform conditions demanded by the glacial-control theory.

The exterior profile of coral reefs.—There is another feature of coral reefs to which Vaughan has called attention as indicating the existence of a submerged platform previous to, and independent of, the formation of the present reefs; this is the continuation of the shallow lagoon floor, not only where it is inclosed by a reef, but also through uninclosed sectors of its area where a marginal reef is wanting. A good number of examples of this kind are known in Fiji; but it is significant that the breach in the reef is in practically all cases on the leeward side. It is further significant that the uninclosed sector, which may like the rest of the lagoon floor have a general depth of 20 or 25 fathoms, slopes gradually to a depth of about 40 fathoms at its free margin and then pitches down with a steep descent to deep water; and it is still further significant that this change of declivity occurs at essentially the same depth as that at which the gentle exterior slope of the reef itself changes to a steep pitch. Instead of regarding these features as indicating the existence of a submerged platform of earlier and independent origin on which the reef was afterward built up, I am inclined to interpret both of them as resulting from aggradation by the transporting agencies of the ocean waters with respect to present ocean-level; in short, as small insular "shelves" of rapid development with respect to the present level of the ocean and therefore as corresponding to great continental shelves of long-continued development with respect to the average relation of land and sea through modern geological periods. The change of slope outside of a continuous reef will be first considered.

Darwin was, I believe, the first to suggest this view as to the origin of the exterior profile of coral reefs in his account of Keeling atoll. "As the external slope of the reef is the same round the whole of the atoll and round many other atolls, the angle of inclination must result from an adaptation between the growing powers of the coral and the force of the breakers and their action on the loose sediments" (74); and he later added, "Considering the manner in which the beds of clean coral . . . . graduated into a sandy slope, it appears very probable that the depth at which reef-

building polypifers can exist is partly determined by the extent of inclined surface which the currents of the sea and the recoiling waves have the power to keep free from sediments" (84), thus foreshadowing a view that is now generally accepted.

A good number of other observers have interpreted the gradual slope and the steep pitch outside of a reef in the same way. Thus we read in the "Challenger" report regarding the reef at Tahiti, "The whole of the space from the edge of the reef to a depth of 35 fathoms was covered with a most luxuriant growth of corals, with the exception of one or two small spaces where there was white coral sand"; the steeper pitch to greater depths was covered by coral blocks, "which have been torn away from the ledge between the edge of the reef and 35 fathoms during storms, or by overhanging masses which have fallen by their own weight. In this way a talus has been formed on which the corals living down to 35 fathoms have found a foundation on which to build further seawards, for this [upper] slope is the great growing surface of the reef."[1] It may be noted that the depth here given for abundant living corals is unusually great, and that Agassiz nearly thirty years later found a smaller proportion of growing corals and a larger proportion of dead corals, coral fragments, and coral sand on the same slope; hence the population of the slope presumably varies in relation to the master-storms of decades and centuries. But the important matter to note here in the present connection is that the outer slope of the reef, like the reef itself and the prograded "belt of low land at the foot of the mountains" of Tahiti, represents an adjustment of aggrading processes and aggraded forms with respect to present sea-level, by whatever changes the present relation of land and sea-level have been brought about.

Gardiner, whose studies of reef slopes are both intensive and extensive, says of the Fiji reefs, "The section outside all is nearly the same, a gentle slope to about 40 fathoms and then a sudden steep."[2]

[1] *Narrative of the Cruise of H.M.S. "Challenger,"* I, Part 2 (London, 1888), pp. 779, 781.

[2] "The Coral Reefs of Funafuti, Rotuma, and Fiji . . . . ," *Proc. Cambr. Phil. Soc.*, IX (1898), 417–503; see p. 445.

The same experienced observer later made a more specific statement regarding the Maldives:

> From the outer edge of an encircling reef flat there is generally to seaward a gradual slope to 30–50 fathoms in 200–400 yards, succeeded by the steep. . . . . This slope is essentially the growing area, being covered almost completely by living organisms. . . . . The outwash of detritus, largely due to undercurrents [or to general agitation by wave and current action, with the result that the finer sediments are chased about until they finally settle in deep water outside the reef where they will not be again disturbed ?], causes a raining down of coral masses and sand over the edge of the steep, carrying it out and allowing the extension of the whole outer side as a fairy ring.[1]

The growth of a reef outward, like a fairy ring, is again mentioned by the same author in his elaborate report on the Maldives.[2] A later statement by the same author is, "The steep . . . . is built up by masses of coral rock from the reef above, its angle representing that at which such material comes to rest in sea-water."[3] It is interesting to add that the change of slope on the exterior of a reef occurs at the same depth as that at which, according to Daly, "the charts of the world show the break of slope" (199) on continental shelves.

Lagoon floors of discontinuous reefs.—As to the free border of an uninclosed lagoon-floor sector, where the inclosing reef is wanting as above mentioned: It is easy to conceive that the lagoon floor there represents a more or less aggraded portion of a pre-existent platform, elsewhere inclosed by a superposed reef; and it is not difficult to explain the origin of the platform by abrasion according to the glacial-control theory as stated by Daly, or to leave it unspecified, except to say with Vaughan that it is independent of the reefs which are growing upon it. But it is also easy to conceive that the lagoon floor of today is the more or less aggraded lagoon floor of earlier days; that the lagoon floor of earlier days may have been deepened during times of rapid subsidence which caused the

[1] "The Origin of Coral Reefs . . . . ," *Amer. Jour. Sci.*, XVI (1903), 203–13; see p. 211.

[2] *The Fauna and Geography of the Maldive and Laccadive Archipelagoes* (Cambridge), I (1903); II (1906); see I, 175, 182, 183, 317.

[3] "The Indian Ocean," *Geogr. Jour.*, XXVIII (1906), 313–32, 454–55; see p. 455. Also "Submarine Slopes," *ibid.*, XLV (1915), 202–19.

upgrowth of a narrow reef, or shoaled during stationary periods and periods of slow subsidence when the reef was broadened; and that the shoaling may have gone so far as to convert a narrow young reef and a deep lagoon into a mature reef plain,[1] if subsidence were long enough in abeyance. It is furthermore easily conceivable that prevalent subsidence may have been for a time neutralized in a phase of no submergence, while the ocean-level was falling as a glacial epoch came on, and then accelerated for a time in a phase of rapid submergence while the ocean-level was rising as a glacial epoch passed off; that a mature reef plain, formed during the neutralized phase of no submergence as a glacial epoch came on, might not be completely rimmed around by a new reef which grew up during the following phase of accelerated submergence as the glacial epoch passed off; and that in such case a failure of growth might reasonably enough take place on the border of the leeward sector of the reef plain, where the quantity of fine sediment shifted about by the waves might very likely prevent or retard coral growth. All of these mental schemes—mere figments of the imagination—are, as is said above, easily conceived by anyone who cares deliberately to consider the coral-reef problem; the difficulty in the problem lies elsewhere, namely, in the discovery of tests by which one of the schemes may be shown to represent better than any other the processes of the invisible past and thus to offer the best explanation for the invisible as well as the visible structures of the present.

The best explanation that I have been able to reach is as follows. First, regarding the exterior profile of continuous reefs: In view of the evidence already given, from which it appears that the production of platforms by abrasion during the glacial period is improbable if not impossible, and in view of the fair accordance between the depths at the outer margin of the uninclosed sector of a lagoon floor and the depth on the outer face of a reef where the change takes place from a gentle slope to a steep pitch, I am persuaded that the change of slope at 40 fathoms is not an inheritance from a time when that part of the reef lay at or close to the surface of the ocean, but, as already stated, a consequence of adjustment between

[1] "The Great Barrier Reef of Australia," *Amer. Jour. Sci.*, XLIV (1917), 339–50; see p. 346.

the detritus to be transported and the agents of transportation with respect to present sea-level. Like the reef itself, the two elements of its exterior profile—namely, the gentler slope down to 40 fathoms and the steeper pitch below—have been brought by organic growth and by inorganic processes into a normal relation to sea-level. Secondly, regarding the free border of an uninclosed lagoon-floor sector of atolls and barrier reefs: In view of the alternate retardation and acceleration of submergence by the combination of prevalent subsidence with the periodic changes of ocean-level during the glacial period—for this is, in my mind, the chief value of the glacial-control theory—I am strongly inclined to regard any "platforms" that may exist, now more or less aggraded, beneath incompletely or completely inclosed lagoon floors as nothing more than the surface of earlier reefs normally broadened while submergence was so slow that narrow reefs were transformed into mature reef plains. Thus interpreted the present reefs are merely new, still young, and relatively narrow growths above their mature predecessors; narrow, because they have been developed while submergence has been accelerated. This inclination of opinion has been strengthened by an examination of charts of submarine banks both within and without the coral seas, and that aspect of the problem must next be examined.

Let it be noted, however, that if the explanation above suggested for the change in the exterior slope of a reef at 40 fathoms depth be correct, then Daly's conclusion that "the present atoll, barrier, and fringing reefs . . . . have been developed nearly or quite in the same interval of time" cannot be supported by the agreement of "their sectional areas and their volumes, as measured, in each case, above the break of slope at the platform on which the crowning reef stands" (233). A further conclusion is also vitiated, namely, that inasmuch as "the surface outcrops and volumes of the greater barrier and atoll reefs, measured from the levels of the lagoon floors, are respectively nearly equivalent in the Pacific and Indian oceans," therefore "the earth's crust must have sunk at a nearly uniform rate throughout the enormous area described . . . . if these reefs were formed by subsidence" (233, 234).

Neither the break of the exterior slope nor the level of the lagoon floor of existing reefs is, as far as I can make out, the record of a former lower sea-level: both appear to have been brought into relation with present sea-level by processes now acting. It certainly seems as reasonable to explain the exterior profile of coral reefs in this way as to explain "the break of slope on the [continental] shelves . . . . near the 40-fathom line" as a result of wave and current action at the present stand of the ocean surface, and therefore since the present stand was assumed.

[*To be continued*]

PERMO-CARBONIFEROUS GLACIAL DEPOSITS OF SOUTH AMERICA

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INTRODUCTION

The proofs of tremendous glaciation at the end of the Carboniferous have been given in great detail from South Africa and Australia and less fully from India; but comparatively little has been reported regarding Permo-Carboniferous glaciation in South America. Having seen something of the tillites and glaciated rock surfaces of typical localities in the first three regions, it seemed desirable to visit the less-known glacial deposits of South America. During the past summer this has been accomplished, and it is proposed to give in this paper a brief account of what was observed.

The probability that certain Carboniferous or Permian bowlder conglomerates with a matrix of shale in southern Brazil were of glacial origin was recognized by Orville Derby as early as 1888;[1] but no striated stones were found, and the evidence seemed scarcely sufficient to establish the point. In 1907 and 1908 I. C. White and David White made it almost certain that the widespread bowlder conglomerates were glacial, the latter showing that the accompanying flora, as collected during I. C. White's examination of the coal deposits of southern Brazil, was identical with floras in a similar relation in South Africa and India.[2] Still the final proof, the finding of striated stones, was lacking.

In 1908 J. B. Woodworth studied the southern Brazilian tillites, finding striated stones plentiful and making their glacial origin absolutely certain. His report on the field work accomplished, with

[1] Orville Derby, "Spuren einer carbonischen Eiszeit in Süd Amerika," *Neues Jahrb. für Min.*, etc., Band II (1888), 175.

[2] David White, "Permo-Carboniferous Climatic Changes in South America," *Jour. Geol.*, XV (1907), 615–33; and I. C. White, in his *Relatorio Final on the Brazilian Coal Fields*, 1908, pp. 11–119.

the aid of two young Brazilian geologists, Eusebio Oliviera and Juvenal Pacheca, is admirable and has served as guide in a portion of my own work.[1] In the following year H. Bross confirmed his conclusions, finding striated stones near Itararé.[2]

Up to 1911 Permo-Carboniferous tillite had been reported from southern Brazil only; but in that year T. G. Halle described tillite of the same age from the Falkland Islands, which may be looked on as belonging to the South American region.[3] In 1912 tillite with polished and striated stones, including bowlders up to 1.5 meters in diameter, was described by C. Guillemain, from Uruguay;[4] and in 1913 J. Keidel announced the finding of tillite of this age in southern and western Argentina in a paper read before the Twelfth Geological Congress in Toronto; while in 1916 he gave an excellent and full account of the tillite at Sierra de la Ventana in southern Argentina.[5]

From this outline of the literature on the Permo-Carboniferous glaciation in South America it will be seen that our knowledge of the distribution of the tillite is rapidly growing, extending now to three countries, and that this glacial formation is widely spread in southern Brazil and perhaps also in Argentina. In Brazil the excellent field work of Oliviera and Pacheca is constantly extending the known area of glaciation, so that in this respect South America may soon rival South Africa and Australia and surpass India.

It was planned to visit localities for tillite in several parts of Brazil and at Sierra de la Ventana in Argentina, and these plans were carried out successfully, largely through the help and advice of Pacheca in São Paulo and of Keidel at Buenos Aires. I am specially indebted to Dr. Pacheca, who has mapped the tillite in detail in the state of São Paulo, and who showed me a number of

[1] J. B. Woodworth, *Bull. Mus. Comp. Zoöl., Harvard*, LVI, No. 1, Geol. Series, X. *Geol. Exped. to Brazil and Chile.*

[2] H. Bross, "Glacial Spuren in Parana," *Cent. Bl. für Min.*, etc., 1909, pp. 558–61.

[3] T. G. Halle, *Geol. Mag.*, N.S., V, 264–65; also *Bull. Geol. Inst., Univ. Uppsala*, XI, 144–56.

[4] C. Guillemain, *Neues Jahrb. für Min.*, etc., Beil. Band XXXIII, 208–64.

[5] J. Keidel, *Comptes Rendus*, pp. 676–80; also in *La Geologia de las Sierras de la Provincia de Buenos Ayres*, Tomo XI, No. 3, *Anales del Ministerio de Agricultura of the Argentine Republic*, 1916.

typical outcrops in the field. Through his courtesy and kindness I had an admirable introduction to the Paleozoic bowlder clays of Brazil.

TILLITES IN THE STATE OF S˜O PAULO

In tropical Brazil, with its moist, hot climate, weathering goes to great depths, and even in the southern parts of the country, where the climate is warm temperate, the products of decay mantle most of the surface, so that fresh outcrops of rock are seldom to be found under natural conditions. On this account the most satisfactory points for geological work are cuttings along the railways or depressions where roads ascend hills and the wheels of vehicles have worn their way downward. To an observer fresh from parts of North America where the Pleistocene glaciation has left clean surfaces of almost unchanged rock this is most disconcerting, and it takes a little time to adjust one's self to the new conditions. The working out of field relations is greatly hampered by the products of weathering, which usually hide even the weathered rock and may accumulate to considerable depths on slopes and in valleys.

Under Dr. Pacheca's guidance a number of railway and road sections were visited to the north of the city of São Paulo, the first region being near the thriving city of Campinas. In railway cuttings two or three kilometers from the city, tillite rests upon gneiss, probably of Archean age, two mounds of the gneiss rising with rounded forms suggesting *roches moutonnées;* but unfortunately weathering has gone so far at the contact as to destroy any smoothed or striated surface that may have existed in the beginning. According to Dr. Pacheca this is almost the only example known in Brazil of tillite resting on what must have been a scoured surface of solid rock.

The tillite is weathered and scarcely harder than certain Pleistocene tills, though its yellow or red or chocolate-brown color is unlike the customary bluish gray of North American bowlder clay. Striated stones were not found here, though the general appearance of the rock was that of tillite, some of the more resistant stones inclosed in it, such as quartzite and granite, still showing subangular forms and smoothed surfaces. Overlying the tillite are shaly or sandy beds, distinctly stratified and including some-

times a thin layer of conglomerate, the series being closely related to the tillite and sometimes interstratified with it, as in many sections of Pleistocene glacial deposits.

The next point visited was near Capivary, reached by a narrow-gauge railway from Campinas, where a delightful walk of 18 kilometers disclosed excellent sections of tillite containing typically shaped and sometimes striated stones (Fig. 1) including

FIG. 1.—From Capivary, São Paulo, Brazil

bowlders of sandstone, quartzite, conglomerate, and granite occasionally reaching a diameter of one meter. The coarse conglomerate forming some bowlders quite suggests the Huronian tillite of Cobalt, Ontario, and their source in Brazil is unknown. The tillite has a thickness of three or four meters and rests on soft, stratified sandstone or sandy shale sometimes cross-bedded. In one place it is covered by a sheet of trap mostly weathered into the bright-red "terra roxa" which forms the best soil for coffee and sugar plantations.

A visit was made to a section near Villa Raffard, about four kilometers southwest of Capivary, to see some large bowlders of

the ancient conglomerate, including pebbles of jasper, another feature suggesting the Huronian rocks of Ontario. These conglomerate bowlders have also been mentioned and figured by Woodworth.

In several places shales accompanying the tillite have been thrown into folds a few meters in dimensions, either by ice-thrust at the time of glaciation or by later compression. Over the tillite in places a brown fine-grained unstratified material, pierced by worm or root holes, stands up as low cliffs and suggests an ancient loess. At one point on the railway near Capivary (kilometers 160–61) shales beneath the tillite appear to have been crumpled and then truncated, showing an unconformity between the tillite and the soft sediments beneath; and some soft sandstone bowlders in the tillite are quite like an irregularly bedded sandstone frequently found in the same position, suggesting the same relationship.

The fresh tillite is often solid enough to make vertical faces in cuttings and shows spheroidal shapes when weathering has begun. Ultimately the rain breaks it down into slippery clay, gray or yellowish or red in color, strongly suggesting a rain-crumbled Pleistocene till. Near the small station Elias Fausto, Dr. Pacheca has found tillite inclosing very large granite bowlders, one partly disclosed measuring $3 \times 3 \times 2$ meters, and looking like one of the Iowan bowlders of the Western states.

My last excursion under Dr. Pacheca's guidance was to Limeira, 50 kilometers northwest of Campinas, where a round of 21 kilometers was made over country roads giving an opportunity to see typical bowlder clay extending over many square kilometers of gently rolling country. The tillite is usually chocolate colored and in places reaches a thickness of 25 meters, while in other places it has been cut through by the stream valleys. In the steep walls of a sunken road leading out of the town plenty of well-striated stones were found, and except for the prevailing red color and a little greater hardness the outcrops reproduce perfectly the features of a region of bowlder clay in North America. It was hard to believe that the rock was as old as the Permian.

Limeira is about in latitude $22\frac{1}{2}^{\circ}$, a degree within the tropics, so that in Brazil, as in India and Australia, the ancient ice-sheet reached much nearer to the equator than any Pleistocene ice-sheet.

It is estimated by Drs. Florence and Pacheca, of the Geological Survey of the State of São Paulo, that the outcrops of tillite extend from northeast to southwest for 500 kilometers, with a width of from 50 to 100 kilometers; and it must be added that the tillite follows the gentle northwestward dip of the rocks of the region and probably extends far beneath the Triassic beds in that direction. It is evident that one is dealing with deposits formed by a great ice-sheet spread out over a peneplained surface and not with the results of mountain glaciers.

TILLITE IN STATES SOUTHWEST OF SÃO PAULO

After the admirable introduction to the study of Brazilian glacial deposits provided by the kindness of Dr. Pacheca there was little difficulty in recognizing the characteristic appearance of the tillite, and on the journey by rail from São Paulo to Montevideo in Uruguay some of the localities described by Woodworth were visited, the first just beyond the southwestern boundary of the state of São Paulo between Itararé and Sengens. In railway cuts near Sengens, Woodworth had found striated stones and large bowlders of sandstone; and a walk along the railway between the two stations proved extremely interesting.[1] Following the crooked narrow-gauge railway from Sengens northeast toward Itararé tillite is seen for eleven kilometers (from km. 241 to km. 230) resting usually on sandstone, occasionally with a hummocky surface and in one case with a suggestion of furrowing in a direction from southeast to northwest or vice versa. The sandstone is still soft, and when the tillite was deposited may have been softer, so that large blocks could easily be lifted and inclosed in the glacial materials. In addition to these masses of local rock there are quite large bowlders of shale and of granite, and a multitude of smaller stones, many of a harder sandstone than the underlying rock, and a few of quartzite. The tillite varies in thickness, sometimes reaching ten meters. Parts of it near kilometer 241 have been more or less

[1] See Woodworth's *Report,* p. 62 and Pls. xxi and xxii.

pushed and crumpled, and not far to the northeast is the great fault and escarpment mentioned by Woodworth.

The best display of tillite is about at kilometer 235, where the smaller stones are very frequently striated, more so than in any other till I have seen, whether Pleistocene or older. Many of the glaciated stones show not only "soles" but well-defined facets, as if they had been firmly held till a face was ground flat and then adjusted at another angle, resulting in another flat face. These facets sometimes come together sharply. In early days similar faceted stones from the Permo-Carboniferous tillite of India attracted attention. It would seem as if the Permo-Carboniferous ice-sheets held their imbedded stones more firmly than those of the Pleistocene. Why? Were their bases colder or was there a greater thickness of ice, giving a stronger pressure?

As may be seen from the train, tillite extends several kilometers on the route southwest; but the next stop was made at Ponta Grossa, midway across the state of Parana, where I. C. White had described outcrops of glacial conglomerate.[1] On the side of the ridge on which the town is built, cuttings, made for streets and for drainage, disclose reddish, sandy glacial deposits containing subangular stones of various kinds, a few of which were found to be striated. A fairly good section is seen also on a road leading into the country. Above the tillite there is a sheet of trap weathering into a very red soil, and beneath it sandstone followed by black shale from which Devonian fossils are reported.

A visit was made also to Serinha, 70 or 80 kilometers to the southeast, where Woodworth suspected an older tillite. Typical bowlder clay is passed between Palmeira and Nova Restingua and may be seen at Porto Amazonas. There is a rapid descent from Palmeira to Serinha, which is in a deep river-valley at the base of sandstone cliffs. The tillite here takes the form of blue or yellow shale, readily weathering to clay, containing subangular stones, chiefly sandstone, quartzite, and granite. No striated stones were found, but the bed looks like a glacial deposit. It is overlain by 200 feet of firm sandstone resembling the rock found beneath the tillite at higher levels. Beyond this fact no clue to its age was

[1] I. C. White, *Relatorio Final on the Brazilian Coal Fields*, 1908, p. 51.

observed. The whole series of rocks, including the two tills, seems to lie nearly horizontal, doubtless with a gentle dip northwestward following the regular trend of the stratification in southern Brazil. The tillite at Serinha looks no older than that described before, and may represent merely a Carboniferous forerunner of the more important glaciation to follow.

Southeast of Ponta Grossa the railway lies too far west to give opportunities of observing the glacial deposits, passing over trap-sheets, Triassic sandstones, etc.; but I. C. White's account of the bowlder conglomerates associated with a low grade of coal and Permian plants in the state of Santa Catharina, e.g., at Orleans, shows that tillite continues to latitude 28°.[1] His map of the Tubarão series, which includes the Orleans glacial conglomerate, extends the tillite to the southern end of Brazil, in Rio Grande do Sul, though his account does not specially mention bowlder conglomerates as having been observed in that part of the country.

Guillemain, by finding tillite with striated stones at Fraile Muerto in northern Uruguay, not far from the boundary of Brazil, as noted in the introduction, continues the region of glaciation still farther to the south. Including the 500 kilometers reported from São Paulo this gives a length of about 1,500 kilometers from northeast to southwest, running in latitude from $22\frac{1}{2}°$ to about $32\frac{1}{2}°$. The tillite has not yet been found to outcrop continuously for this long distance, but the known localities are sufficiently numerous to make its continuity highly probable. Its known width is estimated at from 50 to 100 kilometers in São Paulo, but it is unknown how far it extends beneath the Triassic sediments and trap-sheets to the northwest.

TILLITE IN SIERRA DE LA VENTANA

There is a long gap between the Permo-Carboniferous deposits of Brazil and northern Uruguay and the nearest outcrops of tillite discovered in Argentina, which are in the Sierra de la Ventana not far from Bahia Blanca. Dr. J. Keidel, chief of the Geological Section of the Argentine Survey, was good enough to plan an excursion to this locality for me. A rail journey of 537 kilometers

[1] I. C. White, *Relatorio Final on the Brazilian Coal Fields*, 1908, pp. 11–13 and 51.

southwest from Buenos Aires brings one to the small station among the hills, after passing a vast stretch of prairie-like pampas with few or no outcrops of rock. The Sierra rises as rocky ridges with deep valleys between, one of them followed by the river Sauce Grande and others by its tributaries.

The railway crosses the river just south of the station and follows up the valley of a small stream in the Arroyo Negro. The best exposures of tillite are found in the railway cuttings along the Arroyo within seven kilometers of Sierra de la Ventana, and these will be described first.

The unweathered tillite is dark, bluish gray and entirely different in appearance from the usually red or brown and much-decayed tillite of Brazil. The rock is hard and shows some slaty cleavage, and the stones scattered through it are often a little squeezed or broken and slightly step-faulted. The weathered tillite is greenish or yellowish and crumbles somewhat readily, setting free the inclosed stones, but from the unweathered rock it is difficult to extract them unbroken. The fresh tillite is very like that from some outcrops of the Dwyka in South Africa, where the rock has undergone squeezing and distortion in mountain-building operations; and it closely resembles the Huronian tillite of Cobalt and might easily be taken for it in hand specimens.

The pebbles and bowlders inclosed include several species of rocks, granites and hard sandstones being commonest. They are seldom more than half a meter in diameter and have the characteristic shapes of glaciated stones. A considerable number have well-striated surfaces and are typical products of ice action.

In some of the cuttings cross-bedded quartzite and more or less water-formed conglomerate occur also, apparently interbedded with the tillite; and in several places quartzite overlies the tillite conformably. The base of the tillite was not seen in the railway cuttings, and a search was made for it to the north, where a small stream flows toward the Sauce Grande, but in vain. On this stream the tillite has been squeezed into schist conglomerate with a marked cleavage, reminding one of the Temiscaming and Doré conglomerates of Ontario. A search still farther north showed no solid rock for several kilometers until the base of the northern range

of hills was reached, where quartzite, mica schist, and slate were encountered.

Sections were examined a few kilometers up the river from the station and several fresh-looking outcrops of tillite were found at the water's edge. Ascending the slopes from such outcrops one finds weathered tillite for a few hundred yards, then a cliff of tillite, followed by a covered belt where only quartzite pebbles can be seen for a height of about 15 or 20 meters. A second cliff of tillite reaches 85 meters above the river and is followed by quartzite to the top of the ridge. The lower bed of quartzite seems to be interglacial, corresponding to the band of quartzite and water-formed conglomerate seen in the railway cuttings.

A section a kilometer or two down the Sauce Grande shows no base to the tillite, which has a thickness of 90 meters, as determined by aneroid, and is covered by quartzite including a band of tillite. None of the sections was entirely satisfactory, since on the gentler slopes the solid rock is more or less hidden; but the thickness of the glacial beds seems to be not less than 60 meters and may be much more than that.

An excellent account of the glacial deposits of Sierra de la Ventana is given by Keidel in *La Geologia de las Sierras de la Provincia de Buenos Ayres* (1916), as mentioned in the introduction to this paper; and the statement is made that the origin of a number of the inclosed bowlders is unknown. Keidel puts stress on the resemblance of these deposits to the Dwyka, but gives no proofs of their age except that they are later than the Devonian, as shown by the inclusion of pebbles of limestone with Devonian fossils. The hard and somewhat metamorphosed character of the rock, which seems to suggest a greater age, is to be accounted for by the action of orogenic forces. One of Keidel's plates represents the tillite as somewhat folded in a way that would add to the apparent thickness of the bed, but in my own field work no clear evidence of folding was seen, though compressive action was evident.

TILLITE NEAR SAN JUAN IN WESTERN ARGENTINA

Following a plan suggested by Dr. Keidel an excursion was made to exposures of tillite in western Argentina somewhat south of

San Juan. The nearest point to the outcrops on the railway between San Juan and Mendoza is at Paradero, kilometer 489. The railway traverses a desert country covered with sand and stones with isolated hills of rock not far to the east and the loftier Chico de Zonda, a range of foothills of the Andes, about eight kilometers to the west, as shown on Stappenbeck's geological map of the region. Walking westward over the desert from the railway there is a gentle rise for two or three kilometers, followed by low ridges between profound ravines, apparently cut by temporary streams due to cloud-bursts in the mountains. At about five kilometers west there are steeply tilted red shales dipping westward, followed by hills of a green, basic eruptive, greatly weathered, and then high cliffs of gray limestone. In the latter rock, fragments of crinoids and a syphon of orthoceras were found. It is indicated on the map as Silurian.

A little to the south of this section, where a narrow valley penetrates rugged hills, a greenish-gray shaly or slaty rock occurs, crumbling to fine débris on the surface, and including one or two bands of dark-brown pebbles and larger stones (Fig. 2). Most of the stones are fairly well rounded, as if rolled on a beach or in a river, and many have been broken and recemented. Frequently they have been broken again where they lie on the surface, probably by alternations of heat and cold.

A number of these stones are striated, often on more than one face. The largest seen was half a meter or somewhat less in diameter and was strongly scored. The stones are mainly basic eruptives, quartzite or limestone, the last too much attacked to show marks of glaciation. These stones appear to have been imbedded in the weathered, shaly rock, and in a ravine near by a few isolated ones are found still inclosed. The series appears to be tilted, but the dip and the limits of the bowlder bed could not be sharply determined, and in places two bowlder beds occur separated by a few meters of shale. These outcrops of loose, striated stones were followed for nearly a kilometer in a southerly direction, running parallel to the strike of the rocks in the foothills.

Somewhat to the southwest, where the narrow valley is steep-walled and approaches the cliffs, a side ravine disclosed an abso-

lutely different section, in which a bowlder conglomerate rudely stratified in parts rises as a ridge about 30 meters high. This is of a kamelike character and includes sand, gravel, and stones of all sizes up to a meter in diameter. They are often rounded, but may be of various shapes and consist of many kinds of rocks—granite,

FIG. 2.—From tillite south of San Juan, Argentina

gneiss, quartzite, vein quartz, sandstone, and limestone having been observed. Striated stones seem rare, only one poorly marked one having been found. It may be remarked, however, that in Pleistocene kames also it is unusual to find distinctly striated stones. Beneath the kamelike bed there are two or three meters of sandstone, and across a wide valley to the south a cliff shows six or seven meters of the conglomerate underlying, apparently

conformably, a hundred meters or more of sandstone with a westward dip.

The two types of deposit just described are as different as possible, though both seem to be glacial, but I was unable to determine how they are related to one another, since there has been folding, faulting, and squeezing during the formation of the mountain range, rendering the relationships complicated.

Before leaving Buenos Aires, Dr. Keidel had referred to two tillites, a lower and an upper, corresponding probably to the two deposits just described. He mentioned also that near the lower tillite Talchir plants had been found, and some distance farther south Kharbari plants, giving a clue to the age of the deposits. He has also found tillite to the north of San Juan, reaching in one place latitude 28°, and has discovered a striated surface of Devonian limestone beneath the tillite. Specimens of the tillite and of the glaciated surface are to be seen in the Museum of the Survey on Calle Maypu in Buenos Aires. His account of the very interesting glacial deposits in the western foothills of the Andes must be awaited for details as to their general features and relationships, but I am able to confirm his statements as to the glacial character of the beds so far as seen by myself.

CONCLUSIONS

From the descriptions given it will be seen that there are three widely separated regions of known Permo-Carboniferous glaciation in South America, the deposits differing much in appearance and lithological character, but all showing plainly the effects of ice action. The Brazilian tillites are the most widely distributed and the least changed. They occur along the dissected edge of a tableland rising several hundred meters above sea-level and dip gently inland beneath sandstones and trap-sheets of the early Mesozoic. One or two diamond-drill cores prove that the tillite extends for 50 kilometers or more beneath the Triassic beds, but how much farther they go in that direction is unknown. There can be no doubt that they once reached farther seaward, so that the original ice-covered area must have been much greater than the present known area of tillite. As marine fossils have been found by Oliviera interbedded with the tillite on the Rio Negro in the state

of Parana,[1] we may conclude that the region was at that time not a tableland but a comparatively low plain. In any case the whole character of the widespread, almost flat sheet of tillite in southern Brazil is such as must have resulted from ice action of the continental type. Mountain glaciers could not have provided so extensive, uniform, and relatively horizontal a deposit as the Brazilian geologists have found.

From what center the ice spread out is not known, though the numerous bowlders of granite and gneiss suggest a motion inland from the belt of Archean along the Atlantic coast. In that case the ice-sheet must have extended far toward the southeast, perhaps beyond the present edge of the continent. However, there are granites and gneisses farther west, and outcrops of these rocks which existed in Carboniferous times may lie buried under later deposits toward the west or north. The bowlders of ancient conglomerate containing jasper may some day be traced to their source, giving evidence of the direction in which the ice moved.

As to the tillites of the Rio Sauce Grande and of the belt along the foothills of the Andes near San Juan, the areas known to be covered by them are so small that local mountain glaciation might perhaps account for them; though the fact that tillite of the same age occurs on the Falkland Islands and that a great ice-sheet covering many thousands of square miles reached sea-level a few hundred miles to the north or east suggests that a very large part of South America must have been ice covered. It is not unlikely that the areas of ice action coalesced to form a single great sheet 1,300 miles or more in diameter and covering hundreds of thousands of square miles, something comparable to the vast continental ice-sheets of Europe or North America in the Pleistocene. The northern edge of this ice-sheet reached at least one degree into the tropics in Brazil; and this occurred, not on high mountains, but on comparatively low ground, as shown on a former page.

Recent advances in the study of the South American Permo-Carboniferous glacial deposits bring that continent into the same rank as South Africa and Australia with respect to the area then covered by ice, while India has been much surpassed. The magnitude of the geological problem involved is growing from year to

[1] Woodworth's *Report*, p. 29.

year, and the difficulty of accounting for such tremendous climatic changes is by no means lessening. The fact that the most extensive ice-sheets were in the Southern Hemisphere and that India only in the Northern Hemisphere shows important glaciation at the end of the Carboniferous forms one of the puzzling features of the problem. The idea that a change in the position of the poles could account for Permo-Carboniferous ice-sheets has been completely set aside by the discoveries in South America, since with the South Pole planted in the middle of the Indian Ocean southern Brazil would have been within the tropics.

The theory of glaciation due to elevation is disproved also by the evidence from Australia and South America, showing that the ice-sheets reached sea-level; and in any case it is inconceivable that such vast areas could all be elevated the necessary thousands of feet at the same time. Even if they were sufficiently elevated to give the required temperature, a large enough supply of moisture could hardly be arranged for on the greatly enlarged continents which this implies. The high tableland of the Andes is arid or semi-arid at present, and even the loftier peaks usually show little snow and few and small glaciers. It is evident that elevation alone will not account for the millions of square miles of *nevé* and ice-fields which must have covered much of India, Africa, Australia, and South America.

The most satisfactory theory is that of refrigeration due to changes in the earth's atmosphere; but even this fails to explain why Europe, Northern Asia, and North America should have been so little affected when great regions in other parts of the world were powerfully glaciated. One would expect that the change of climate affecting the tropics in India, Australia, and South America, and probably also in Africa would have been felt everywhere. It may be, however, that while the refrigeration was universal the supply of moisture necessary to form glaciers was lacking in Northern Asia, Europe, and North America. They may have had no ice-sheets for the same reason that Siberia was left uncovered with ice in the Pleistocene Ice Age; because the position of the open seas and the direction of the atmospheric circulation made them relatively dry regions with little snowfall.

THE SUBPROVINCIAL LIMITATIONS OF PRE-CAMBRIAN NOMENCLATURE IN THE ST. LAWRENCE BASIN

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INTRODUCTION

The detailed geological work carried on in recent years throughout the southern part of the Canadian pre-Cambrian shield has shown that the geological succession in the ancient terranes of this territory is regionally less uniform and includes a greater number of rock series than was formerly supposed. Moreover, it has become evident that the widespread correlations implied by the use of the same nomenclature nearly everywhere throughout this great pre-Cambrian province assumes much more with regard to the regional succession in these ancient rocks than is actually known.

Although it is not possible generally to demonstrate with mathematical conclusiveness that geological formations occurring in different localities are equivalent, nevertheless the premature use of the same name for formations, the correlation of which is open to question, or the continued use of the same name for formations after it has become evident that their correlation is in doubt, is misleading, and is an obstacle rather than an aid in geological investigation. Hypothetical correlations of groups of rocks occurring in widely separated districts may serve for comparison or as a stimulus to investigation, but all the advantages of such tentative correlations may be attained by using a general terminology (Proterozoic, Archaeozoic, etc.) and thereby avoiding the definite correlations implied in the use of names of local origin. In the pre-Cambrian province which occupies the northern part of the St. Lawrence River basin there are four geographically and geologically separate subprovinces: (1) the region northwest of

[1] Published with the permission of the Director of the Geological Survey of Canada.

Lake Superior, (2) the region south of Lake Superior, (3) the region extending northeastward from Lake Superior and Lake Huron to Lake Timiskaming and Lake Mistassini, and (4) eastern Ontario and the lower St. Lawrence, with which might be included the Adirondack region. With the possible exception of some of the late pre-Cambrian series occuring in the Lake Superior and the Timiskaming subprovinces, the evidence upon which the rocks of these separate regions can be correlated is exceedingly meager, and for the present, at least, the only logical course would seem to be to build up a separate nomenclature in these various subprovinces by using those names already defined in these localities, supplemented by such local new names as become necessary from time to time as geological investigation is continued.

OBJECTIONS TO AN INTER-SUBPROVINCIAL NOMENCLATURE

The widespread correlations implied in the use of a common nomenclature throughout all the pre-Cambrian subprovinces of the St. Lawrence basin has been based on the assumption that the succession of formations within the various subprovinces has been worked out to practical completeness, and on the application of certain principles by which the correlation of the various formations in these widely separated areas is presumed to be established. The purpose of the following discussion is to point out that the assumption that our knowledge of the succession of formations in any of the subprovinces is complete is open to question and that the principles by which pre-Cambrian rocks are generally correlated are in part inapplicable and as a whole quite inadequate for the establishment of a pre-Cambrian nomenclature embracing all the territory in the St. Lawrence basin in which pre-Cambrian rocks occur.

OUR KNOWLEDGE OF THE SUCCESSION OF FORMATIONS IN THE SUBPROVINCES INCOMPLETE

The numerous regional classifications of the pre-Cambrian rocks of the St. Lawrence basin which have appeared from time to time in recent years, and the use of such terms as Keewatin, Laurentian, and Huronian nearly everywhere throughout this great pre-

Cambrian province and at points hundreds of miles from those in which these names were originally defined, would seem to imply that our knowledge of the succession of formations within this vast territory was much more complete than is actually the case. Only a very small part of the territory in the St. Lawrence basin in which pre-Cambrian rocks occur has been actually mapped in detail, and even in those localities which have been mapped in considerable detail and have been regarded in the past as type areas the succession of formations formerly supposed to be present has in many cases been considerably modified by more recent investigation.[1]

THE PRINCIPLES OF PRE-CAMBRIAN CORRELATION INAPPLICABLE OR INADEQUATE

Continuity or approximate continuity of outcrop.—The principle of continuity, or approximate continuity, of outcrop is the most conclusive of all the means by which the relationship of rocks can be determined. But it is inapplicable to the correlation of the various rock series occurring in the different pre-Cambrian subprovinces for the reason that these are geographically and in part geologically separate from one another. Between the Timiskaming and the Grenville subprovinces there intervenes an extended belt of banded gneisses; between the Timiskaming and the western subprovinces there are the little-known wooded pre-Cambrian highlands on the north and overlapping Paleozoic sediments on the south; and between the northwestern and the southwestern subprovinces lie the waters of Lake Superior. If, therefore, a common nomenclature be employed for all the pre-Cambrian subprovinces of the St. Lawrence basin, this nomenclature must be based on other less conclusive principles of correlation.

Lithological similarity.—This criterion has been widely applied in the correlation of pre-Cambrian formations, although it is in reality of very limited application; for the pre-Cambrian rocks of

[1] A. C. Lawson, *Geol. Surv. Can., Mem. 28*, 1912, and *Mem. 40*, 1913, p. 4.

W. G. Miller and C. W. Knight, *Ann. Rep. Ont. Bureau of Mines*, XXII, Part 2, 1914.

R. C. Allen and L. P. Barrett, *Jour. Geol.*, XXIII (1915), 689.

W. H. Collins, *Geol. Surv. Can., Sum. Rept.*, 1916, p. 183.

C. R. Leith and R. C. Allen, *Jour. Geol.*, XXIII, 703.

the Canadian shield, both sedimentary and igneous, are for the most part common types which might be deposited or intruded or extruded in any epoch of earth history. It has been largely on the basis of this principle that the name Keewatin, first applied by Lawson to the metamorphosed basal volcanic complex occurring in the region northwest of Lake Superior, was extended, first to the Timiskaming region and later to eastern Ontario, a district nearly 1,000 miles distant from the locality in which the term was originally defined; yet volcanic rocks of this character are among the most common in the earth's crust. They are represented at some point in nearly all the pre-Cambrian series of the St. Lawrence basin; are likewise abundant in later formations throughout the world, as in Great Britain, where they occur at numerous horizons ranging in age from the early Palaeozoic to the Tertiary; and are in process of formation at one or more points on the earth's surface today. As a consequence of this unscientific method of correlation the name Keewatin, although presumed to represent a definite formation, in reality is now applied in the Canadian pre-Cambrian subprovinces to any highly metamorphosed volcanic rock without regard to age.

Similar stratigraphical succession of beds.—The larger part of the pre-Cambrian surface rocks of the region under consideration are volcanic flows or clastic sediments, in which a regular sequence of strata is uncommon, and this criterion is therefore inapplicable except to the late pre-Cambrian rocks. It has been especially useful in the mapping of the Huronian series in the Timiskaming subprovince, the Lower Marquette in the region south of Lake Superior, and the Animikie sediments in the region northwest of Lake Superior.

Similar serial succession.—The widespread correlation implied in the nomenclature applied to the pre-Cambrian rocks of the St. Lawrence basin has been based to a considerable extent on this principle, although the apparent similarity in the serial succession may very frequently be explained in other ways. The principal objection to the use of this criterion is that it neglects to consider the possibility of overlap. Sedimentary rock series are not generally deposited continuously or uniformly over immense areas, and

where they have been deposited they are very commonly swept away in part by later erosion, before succeeding series are laid down. Moreover, the pre-Cambrian surface rocks are to a large extent volcanic flows or land sediments, and on this account are much more discontinuous than sediments of marine origin.

Mode of origin of formations.—This criterion is of limited application; for sediments originating in the same way may be deposited during different geological epochs, and likewise sediments originating in different ways may be deposited contemporaneously in adjoining localities. It might be of value in the correlation of certain uncommon types, such as glacial deposits, which generally occur only at long intervals in geological time.

Relationship to batholithic intrusions.—The relationship of the pre-Cambrian surface rocks to the great epochs of batholithic invasion is of great assistance in correlation and may possibly eventually prove to be the most important of all the criteria used in the classification of the pre-Cambrian rock series into major groups; for geological investigation throughout the world has shown that batholithic intrusions are an accompaniment of mountain-building movements in the earth's crust, and are thus directly related to the great regional changes in rock structure, to regional metamorphism, and to the uplifts which give rise to the great erosion intervals which form the dividing lines between the great pre-Cambrian terranes. Some of the applications and limitations of batholithic invasion in rock correlation are included in the following:

Batholithic massifs are co-extensive with the mountains they underlie, and since mountains are generally extensive and linear the massif should also be extensive and linear. The extent of the outcrop of the massif will depend, of course, on the extent to which unroofing has been carried. In the Rocky Mountains, for example, unroofing has apparently only begun; in the Coast Range batholith of the Pacific Coast, on the other hand, unroofing is almost complete; and in some of the pre-Cambrian batholiths of the Canadian shield not only is the unroofing largely completed, but the batholith has also been reduced to base level.

If two batholithic massifs have been intruded in a given region the younger may displace the first. Hence the conspicuous

structural features of the region would be those of the younger massif, and all evidence of the former presence of the older batholith might be destroyed except for such remnants as happened to remain in association with the roof rocks in the geosynclinal belts.

Mountain-building periods and hence also periods of batholithic intrusion occur at long intervals separated by erosion periods and the development of peneplains.

The rocks in the vicinity of an intrusive batholithic mass are generally highly folded and metamorphosed; hence, if in a given area in the vicinity of a batholith flat-lying rocks occur which have not been greatly metamorphosed, it may be inferred that they have not been intruded by the batholith.

Batholiths are composite, and their intrusions continue during long intervals of time so that their various parts are only approximately of the same age.

Batholithic rocks are lithologically so similar that it is generally impossible to distinguish between batholiths of different ages except by means of their relationships to other rocks of which the age is known.

Recently A. C. Lawson has contributed an interesting paper to the discussion on the "Correlation of the pre-Cambrian Rocks of the Region of the Great Lakes," in which he formulates the hypothesis that throughout the region extending from the Adirondacks to northwestern Ontario there were in pre-Cambrian time "two and only two periods in which great granitic batholiths were developed in the earth's crust." On the basis of this hypothesis he correlates all the pre-Cambrian rocks occurring in the territory to which his hypothesis is applied.[1] This hypothesis, if true, would undoubtedly greatly simplify the problems of pre-Cambrian nomenclature and correlation in the region under discussion; but an examination of the hypothesis from either a deductive or an inductive standpoint seems to indicate that it is an unwarranted assumption.

The principal fact on which Lawson's hypothesis of two and only two periods of granitic batholithic intrusion was based was that at the time the hypothesis was formulated only two periods

[1] *University of California Publications*, X (1916), 1–19.

of batholithic intrusion had been recognized in most of the pre-Cambrian subprovinces of the St. Lawrence basin. There is a very apparent reason, however, why two and only two batholithic intrusions can be recognized in a single locality, namely, that if a third batholith were intruded in a district where two batholiths were already present the evidence of the former presence of one or other of the older batholiths would probably disappear.[1]

If it be assumed that batholithic intrusions represent the interior portions of mountain chains it is obvious that the prolonged erosion, which generally follows an orogenic uplift, must inevitably result in the stripping off of the roof rocks from the underlying massif and the replacement of surface rocks by plutonic types in the district where the uplift has occurred; also that successive crustal movements of the orogenic type in the same or adjoining localities must eventually bring about the disappearance of all trace of rocks originally present in such zones of disturbance. It is probable that within the base-leveled pre-Cambrian complex which underlies the larger part of the Canadian shield evidence of the presence of more than two separate periods of batholithic intrusion would not generally survive in a single locality. If, however, the succession of formations can be determined over an extended area, as where less metamorphosed late pre-Cambrian sediments occur, the number of batholithic intrusions which can be recognized might be increased. Thus, as a result of the more extended areal geological studies of recent years, evidence is accumulating that at least three definite periods of batholithic invasion are represented in several of the pre-Cambrian subprovinces of the St. Lawrence basin.

The folded and metamorphosed pre-Cambrian rocks occurring along the southern margin of the Canadian shield have in the main a northeasterly structural trend; likewise the granitic batholiths, so far as their areal distribution has been determined, are distributed in northeasterly trending zones; thus the region (approximately 1,000 miles in length) extending from the Adirondacks to the Lake of the Woods, to which Lawson's hypothesis has been applied, lies almost transverse to the regional trend of pre-Cambrian folding,

[1] A. C. Lane, *Am. Jour. Sci.*, XLIII (1917), 42.

mountain building, and batholithic invasion. Moreover, mountain systems throughout the world are generally narrow and linear and, where zones of crustal disturbance composed of several mountain systems, such as the cordillera of North America, occur, the systems composing the zone are generally of varying age. Hence, if granitic massifs represent the interior of mountain systems exposed by denudation, it is more probable that the northeasterly trending pre-Cambrian batholithic zones of the St. Lawrence basin, instead of belonging to two and only two periods of batholithic intrusion, in reality represent several periods of batholithic development.

Relationship to igneous intrusions other than batholith.—Igneous intrusions other than batholiths, especially if they are composed of unique rock types, can likewise be employed for purposes of correlation, but generally only within a single subprovince. The principle has been used for inter-subprovincial correlation in the case of the late pre-Cambrian diabase intrusions, however, all of which have been generally regarded as Keweenawan in age.

Folding and metamorphism.—Since folding and metamorphism are accompaniments of mountain building and batholithic invasion, these criteria are in reality included under the head, "Relationship to Batholithic Intrusions." It can be generally inferred that in the same district those rocks which are most highly folded and metamorphosed are the oldest in age. This does not follow in the case of widely separated regions, however; for it has been found that rocks which are flat-lying and slightly metamorphosed in one district may be highly folded, metamorphosed, and intruded by granite batholiths in another locality.

CONCLUSION

From the preceding discussion the following conclusions may be inferred: that the regional succession of formations within the pre-Cambrian of the St. Lawrence basin has not yet been sufficiently worked out for the establishment of a definite nomenclature applicable to the whole of this territory; that, since the St. Lawrence basin extends for approximately 1,000 miles in a direction transverse to the trend of pre-Cambrian mountain building and batholithic intrusion, it is theoretically improbable that the

geological history of the various parts of this territory in pre-Cambrian time would be the same; that the geological succession of formations so far determined to be present in these various parts indicates that their history has not been the same; that the pre-Cambrian formations occurring in the St. Lawrence basin fall naturally into a number of separate subprovinces; and that it is advisable for the present that a separate nomenclature be employed in each of these subprovinces.

The principal advantages that might be attributed to the widespread correlations implied in the present nomenclature applied to the pre-Cambrian rocks of the St. Lawrence basin are that they serve as tentative hypotheses for the investigator in the field, and as summaries of existing knowledge for the science as a whole. But it is doubtful whether tentative hypotheses have a place in geological nomenclature, and furthermore, for the investigator familiar with the facts in the field, tentative correlation tables indicating the most probable relationships of the formations occurring in the various subprovinces can afford all the advantages of a regional nomenclature, and for those not familiar with the facts in the field a general classification from which names of local origin are excluded could be used. Such a classification might be less definite, but it would be scientific, since it would express what is actually known, or what is at least generally accepted, by those familiar with the facts in the field rather than tentative hypotheses.

CORRELATION OF THE EARLY SILURIAN ROCKS IN THE HUDSON BAY REGION[1]

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The oldest rocks of Silurian age known in the Hudson Bay region are present in the banks of Nelson River, about forty-five miles above tide-water. The best exposure is about four miles below the outcrop of Richmond strata at the lower Limestone Rapids of the river, where a vertical ledge outcrops to a height of 28 feet above low water. The rocks are nearly horizontal or gently undulating, and consist of yellowish-brown, rather fine-grained dolomite, in layers 4 to 10 inches thick. Masses of this dolomite form a pavement along the banks of the river at intervals for several miles below the main exposure, indicating that the river is actively cutting into these strata in places east of their actual outcrop.

The fossils in this dolomite appear to be restricted to a narrow zone in the lower part of the bed. The most abundant are molds and casts, mostly of the ventral valve, of shells of the species described by Whiteaves as *Conchidium decussatum* from the basal Silurian strata at the Grand Rapids of Saskatchewan River. These shells are in places so crowded together as to make up the greater part of the rock layers, just as they occur at the Grand Rapids outcrop, where they are also restricted to a narrow zone.

The shells of this species found in the Nelson River region show a wide variation in the ratio of their length and width, in the degree of convexity or galeation of the ventral valve, and in the development of the mesial fold on the ventral valve. Some of the partially exfoliated shells even show a distinct mesial sinus extending from the beak over the umbonal region of the ventral valve, which becomes obsolete or is transformed into a mesial fold in the middle

[1] The strata discussed in this paper probably fall within the later half of the Oswegan series of the New York Classification.

and anterior portions of the valve. Similar variations occur in the shells of this species found at the Grand Rapids of the Saskatchewan River, described by Kindle[1] as follows:

> *Conchidium decussatum* belongs to a group of shells in which the specific characters are very plastic. . . . . The ventral valve shows three well-marked types of contour, viz.: (1) Strongly convex with a more or less clearly defined median ridge extending from the umbonal region to the front of the shell. (2) Very convex with tumid umbonal region rounding regularly from the median region to the lateral and anterior margins without trace of median ridge. (3) Strongly convex in median and anterior region with or without median ridge, but with a broad shallow sinus extending from the beak across the umbonal region. These three types of contour make striking contrasts when individuals in which they are best developed are compared; but the intermediate forms, in which neither the presence of ridge or sinus nor their entire absence can be positively stated, make difficult any attempt to discriminate them as distinct varieties.

It is noteworthy that the shells showing a mesial sinus in the umbonal region of the ventral valve are young forms, and the writer is convinced that the more striking differences shown in the ventral valve of this species represent different growth stages in the individuals; the youthful stages show a mesial sinus from the beak across the umbonal region or farther anteriorly, while in the old stages the mesial sinus has disappeared and a distinct mesial fold is frequently developed.

The above-mentioned characters are the principal ones on which Twenhofel founded the genus *Virgiana*, and it seems certain that the species formerly known as *Conchidium decussatum* really belongs to the genus *Virgiana*. Through the kindness of Dr. Kindle a comparison was made of the shells of this species from Nelson River with those from the Saskatchewan region in order to make sure of the identity of the species from the two localities. The shells from the Grand Rapids locality also show unmistakably the characters of the genus *Virgiana*[2] to which this species is here referred.

[1] E. M. Kindle, "Notes on the Geology and Paleontology of the Lower Saskatchewan River Valley," *Geol. Surv. of Canada, Mus. Bull. No. 21* (Geol. Series No. 30), October 14, 1915, p. 16.

[2] Specimens of these shells were also sent to Dr. Twenhofel, the author of the genus, who agreed with the writer that they were true *Virgianas*.

The variation presented in the ventral valve of this species is similar to that shown in the shells described by the writer as *Virgiana barrandei* var. *mayvillensis*, and *V. barrandei* var. *major* from the Mayville limestone in Wisconsin. At the time those varieties were described the only other known representatives of this genus were *Virgiana barrandei* and a variety of that species occurring in the Becsie River (earliest Silurian) formation of Anticosti Island, from which it was thought that they might have been derived. However, the *Virgiana* shells from Wisconsin are now known to be more closely related to *Virgiana decussata* than to the Anticosti forms. In recognition of this relationship it is here proposed to elevate the varieties *Virgiana barrandei* var. *mayvillensis* and *Virgiana barrandei* var. *major* to the rank of species. The former differs from *Virgiana decussata* in having somewhat fewer and coarser radiating plications, less numerous concentric markings, and usually is relatively wider in the anterior part of the shell. *Virgiana major* is a larger shell than *V. decussata*, and generally has a much more strongly developed keel-like median ridge on the ventral valve.

Regarding the age of the strata containing these shells in the Grand Rapids region Kindle[1] says:

> Close comparison between the faunas of the Grand Rapids section and those of eastern Silurian sections, owing to the dearth of common species, is difficult. The dominance in the lowest (Silurian) fauna of this section of such a genus as *Conchidium*, however, makes it probable that the base of the section represents a Silurian horizon not earlier than the Clinton, and probably of early Niagaran age.

This argument is no longer applicable, since instead of belonging to the middle Silurian genus *Conchidium*, the species in question belongs to the genus *Virgiana*, which is an early Silurian genus known elsewhere only from strata of pre-Niagaran (Alexandrian) age.

The early Silurian age of the strata containing *Virgiana decussata* in the Grand Rapids of the Saskatchewan and the Hudson Bay regions can be shown by their relations to associated strata in different areas. In the Grand Rapids region the layers containing *Virgiana decussata* are succeeded by strata which contain the fossils

[1] E. M. Kindle, *op. cit.*, p. 9.

Pterinea occidentalis, *Isochilina grandis* var. *latimarginata*, and *Leperditia hisingeri* var. *fabulina*. In the Hudson Bay region a zone a few feet above the horizon of *Virgiana decussata* furnished shells of *Camarotoechia? winiskensis*, *Pterinea occidentalis*, *Isochilina grandis* var. *latimarginata*, and *Leperditia hisingeri* var. *fabulina*. In the northern peninsula of Michigan[1] early Silurian strata containing *Camarotoechia? winiskensis*, *Isochilina grandis* var. *latimarginata*, and *Leperditia hisingeri* var. *fabulina* overlie the strata containing *Virgiana mayvillensis*, which is a near relative of *Virgiana decussata*. In eastern Wisconsin *Virgiana mayvillensis* occurs in the uppermost layers of the Mayville limestone above which there is a stratigraphic break, the horizon of *Camarotoechia? winiskensis*, *Isochilina grandis* var. *latimarginata* and *Leperditia hisingeri* var. *fabulina*, present farther east in northern Michigan, having been removed by erosion. However, there is no doubt that the strata which in northern Michigan contain *Virgiana mayvillensis* correspond in age to those containing the same species in the upper part of Mayville limestone in Wisconsin, as they are clearly a northeastward continuation of the same beds. The relations of the strata containing *Virgiana* to the overlying and underlying beds in the regions above described are shown in the columnar sections in Fig. 1.

In Wisconsin there was found in the quarry near Peebles a zone only a few feet below the horizon of *Virgiana mayvillensis* and apparently conformable with it, which yielded such characteristic Edgewood species of fossils as *Dalmanella edgewoodensis*, *Rhynchonella? janea*, *Rhynchotreta parva*, and *Atrypa putilla*. The position of *Virgiana mayvillensis* in Wisconsin in the upper part of the Mayville limestone, which at a slightly lower level contains a characteristic Edgewood fauna, indicates that this horizon is Alexandrian (late Edgewood) in age. It is also significant that the strata containing *Virgiana mayvillensis* in Wisconsin seems to occupy about the same position in the Silurian column as do the strata which contain *Virgiana barrandei* in the Becsie River formation of Anticosti Island.

[1] T. E. Savage and H. F. Crooks, "Early Silurian Rocks of the Northern Peninsula of Michigan," *Am. Jour. of Science*, XLIV (January, 1918), 59–64. In the lists of fossils given in this paper the name of the species given as *Atrypa putilla* should have been written aff. *Atrypa putilla*.

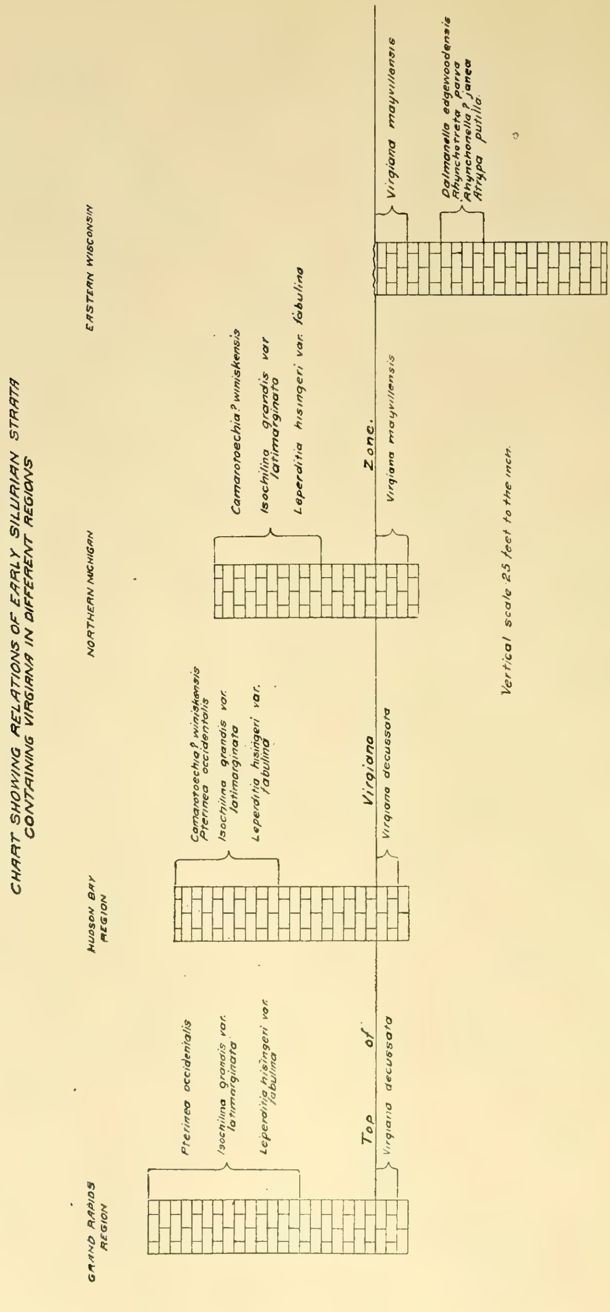
CHART SHOWING RELATIONS OF EARLY SILURIAN STRATA
CONTAINING VIRGIANA IN DIFFERENT REGIONS
GRAND RAPIDS REGION
HUDSON BAY REGION
NORTHERN MICHIGAN
EASTERN WISCONSIN
Pterinea occidentalis
Isochilina grandis var. latimarginata
Leperditia hisingeri var. fabulina
Camarotoechia ? winiskensis
Pterinea occidentalis
Isochilina grandis var. latimarginata
Leperditia hisingeri var. fabulina
Camarotoechia ? winiskensis
Isochilina grandis var latimarginata
Leperditia hisingeri var. fabulina
Top of Virgiana Zone.
Virgiana decussata
Virgiana decussata
Virgiana mayvillensis
Virgiana mayvillensis
Dalmanella edgewoodensis
Rhynchotreta parva
Rhynchonella ? janea
Atrypa putilla
Vertical scale 25 feet to the inch.

Fig. 1

In Michigan the strata containing *Camarotoechia? winiskensis*, *Isochilina grandis* var. *latimarginata*, and *Leperditia hisingeri* var. *fabulina* conformably overlie the *Virgiana mayvillensis* beds, and thus are thought to correspond in age to about that of the Sexton Creek or Kankakee limestone which overlies the Edgewood in Illinois and Missouri, but they were deposited in a different geologic province.

The close correspondence in the fauna of the strata overlying the *Virgiana mayvillensis* zone in northern Michigan with that of the strata above the horizon of *Virgiana decussata* in the Hudson Bay and Saskatchewan regions leaves no doubt of the equivalence of the strata containing this fauna in the areas above mentioned. They also prove that the *Virgiana mayvillensis* zone in Wisconsin and Michigan, and the *Virgiana decussata* zone in the Hudson Bay and Saskatchewan localities represent the same stratigraphic horizon.

Besides the above-mentioned localities Hume[1] has found early Silurian strata containing *Camarotoechia? winiskensis*, and numerous ostracods in the Lake Timiskaming area that he correlates with the Cataract formation, which doubtless corresponds with the *Camarotoechia? winiskensis*, *Isochilina*, and *Leperditia* horizon in the regions above described. The age assigned to this horizon by Hume agrees with that given by the writer above.

Kindle[2] found Silurian strata several hundred miles north of the Grand Rapids locality, in the vicinity of the Pas, from which he obtained the fossils *Camarotoechia? winiskensis*, *Pterinea* cf. *occidentalis*, and *Leperditia* cf. *hisingeri*. This fauna also indicates a horizon about equivalent to that of the Silurian in the Lake Timiskaming region and to the strata containing *Pterinea occidentalis*, *Isochilina*, and *Leperditia*, above the *Virgiana decussata* horizon in the Grand Rapids section, the latter horizon not being exposed in the more northern locality. From the similarity in the faunas of the *Virgiana* zone, and of the higher strata containing

[1] G. S. Hume, "Paleozoic Rocks of Lake Timiskaming Area, *Geol. Surv. of Canada*, *Sum. Rept.* (1916), pp. 188–92. Fossils reported by Charles Schuchert in a personal letter.

[2] E. M. Kindle, *op. cit.*, p. 12.

Camarotoechia? winiskensis, *Isochilina grandis* var. *latimarginata*, and *Leperditia hisingeri* var. *fabulina* in the regions above described it is inferred that during the time these strata were laid down the above-mentioned regions were a part of the same province or basin of deposition, which was rather broadly connected northward with the Arctic Ocean.

This extensive northern invasion, together with the nearly synchronous deposits of the Cataract formation in a basin connected eastward with the Gulf of St. Lawrence region, and of the Brassfield and Sexton Creek limestones which were deposited in a southern basin, indicates a much more extensive submergence of the continent during early Silurian (late Alexandrian) time than was formerly supposed.

The very close correspondence of the middle and late Ordovician and early Silurian rocks and faunas in the Saskatchewan and Hudson Bay regions is strong evidence that they were deposited in a sea that was continuous between these areas. The presence of middle Ordovician and early Silurian rocks and faunas in the Lake Timiskaming region[1] similar to those in the Hudson Bay region, and of late Middle and Upper Devonian strata in the vicinity of James Bay which probably originally extended south to the Timiskaming region,[2] indicates that this part of the ancient Laurentian or Canadian shield did not exist continuously as a land surface throughout the Paleozoic era, as has generally been assumed, but that during middle and late Ordovician time, in early Silurian, and probably also during late Middle and Upper Devonian time the northern seas, temporarily at least, covered the greater part of this shield on the south and probably also on the west of Hudson and James bays. Kindle and Burling[3] have previously shown that the seas probably also extended widely over the Laurentian upland southeast and east of Hudson Bay during the Paleozoic era.

[1] M. Y. Williams, "The Ordovician Rocks of Lake Timiskaming," *Geol. Surv. of Canada, Mus. Bull. No. 17* (Geol. Series No. 27), June 7, 1915.

[2] G. S. Hume, "Paleozoic Rocks of Lake Timiskaming Area," *Geol. Surv. of Canada, Sum. Rept.* (1916), p. 190.

[3] E. M. Kindle and L. D. Burling, "Structural Relations of the Pre-Cambrian and Paleozoic Rocks North of the Ottawa and St. Lawrence Valleys," *Geol. Surv. of Canada, Mus. Bull. No. 18* (Geol. Series, No. 28), July 23, 1915.

NOTES ON SEDIMENTATION IN THE MACKENZIE RIVER BASIN[1]

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INTRODUCTION

In the course of field work in the Mackenzie River region during the summer of 1917 the writer had an opportunity to observe various features in connection with the constructive and destructive work of the rivers and lakes traversed. The following notes relate to the lower Peace, the Slave, Athabasca, and upper Mackenzie rivers, and Great Slave and Athabasca lakes (Fig. 1). The making of these observations was incidental to other work, and they are assembled here as a fragmentary contribution to a knowledge of present-day work in continental sedimentation in the Northwest.

The parallel streams of clear and muddy water in the channel of the Mackenzie, its sloping bowlder-paved banks in marked contrast with the cut banks of the Peace and Slave rivers, and its relatively straight course are among the noteworthy features of this great river. The marked inequality in the rate of sedimentation on opposite sides of Great Slave Lake is one of the significant features in connection with the lacustrine sedimentation of the region. These and other factors relating to sedimentation in the Mackenzie basin will be discussed in the following notes.

MATERIALS OF THE VALLEY FLOORS

The valleys of the Peace and Athabasca rivers are throughout the major part of their courses cut deeply into the shales and sandstones of the Cretaceous formations. At Peace River crossing the Peace River flows in a steep-sided valley cut about nine hundred

[1] Published with the permission of the Director of the Geological Survey of Canada.

feet below the surface of the Cretaceous plateau. The Athabasca, where it joins the Clearwater, has cut its valley into the Cretaceous rocks to a depth of about five hundred feet. The lower portions of both streams, however, flow for considerable distances across a very broad, low, flat plain of recent origin, which is composed

FIG. 1.—Sketch map of the Mackenzie River basin

chiefly of fine silts and sands. These beds are of both lacustrine and fluvial origin and evidently of postglacial age. Near the river the fluvial beds are more in evidence than the lacustrine, but the latter probably have a far greater extent than the former. In the Peace River region the cut banks of sand rising in places 80 feet high or more above the water represent the bottom deposits of a

greater Lake Athabasca which was a contemporary of Lake Agassiz. Similar beds occur along the lower Slave River (Fig. 2), which belong to the period when a much greater Slave Lake was developing the

FIG. 2.—Lacustrine sediments on the Slave River near Salt River, representing deposits of a former greatly extended stage of Great Slave Lake. Photograph by E. J. Whittaker.

wave-cut cliffs and elevated beaches now found far back from its shores. The following section, taken above Little Rapids on the Peace, indicates the general character of these lacustrine beds:

1. Forest bed and soil	1 foot
2. Brown sand	3 feet
3. Forest bed, etc	6 inches to 0
4. Gray sand with pebble band in middle	1 foot
5. Hard sand with limy bands	1 foot
6. White marl	8 inches to 0
7. Gray sand with calcined roots	$2\frac{1}{2}$ feet
8. Marly sand	2 inches
9. Gray even-bedded sand partly covered	30 feet

The broad low plain of lacustrine sands which have been extensively re-worked by the river, extends from the pre-Cambrian hills east of Slave River and the lower Athabasca many miles to the westward. It meets the foot of a plateau called the Caribou Mountains west of the Slave River, while a similar upland known

as the Birch Mountain projects shieldlike from the south into the low land between the Peace and the Athabasca rivers.

The banks of the Mackenzie for the first 200 miles below Great Slave Lake are in some places very low, particularly near the head of the river, though rising 50 to 150 feet above the stream in many places. But the materials in which the channel is cut are nearly everywhere either glacial drift or Devonian shales. It will be pointed out later that the till banks of the Mackenzie give rise to certain peculiarities of the river which are not found in the Slave, lower Peace, and Athabasca rivers, whose channels are cut largely in lacustrine beds.

RELATIVE TURBIDITY

The major part of the great volume of water comprising the upper Mackenzie River is gathered by two large rivers, the Peace and the Athabasca. The latter stream is filtered through Athabasca Lake before joining the Peace. The Peace, united with the Athabasca under the name of the Slave River, pours its flood of sediment-laden water into Great Slave Lake, which discharges it, freed of its burden of floating trees and suspended mud, into the head of the Mackenzie River. The filtered waters of the Slave and half a dozen other considerable streams which flow into Great Slave Lake unite in the upper Mackenzie to form a stream which, in both volume and clarity, is comparable with the upper St. Lawrence. This clear river issuing from the lower end of Great Slave Lake receives no stream of notable size for 150 miles, to the point where it is joined by the Liard from the west. The Liard drains a great area including all the easterly valleys of the Rocky Mountains between the head waters of the Peace and the Yukon. The large volume of the Liard is characterized by a high degree of turbidity. Its muddy waters join the clear waters of the Mackenzie at Fort Simpson, but for more than 160 miles below Simpson they fail to mix except in a limited zone near the middle of the river. During the canoe trip down the Mackenzie observations regarding the relative clarity of the water on the two sides of the river were made repeatedly. The following excerpts from my notes indicate the contrasts observed. Twenty-five miles below the mouth of the Liard River, a crossing from the east to the west bank was made to

observe the relative amounts of sediment on the two sides. On the east side the water was quite clear, the tip of an oar being visible as far down as its length. One third of a mile from the east bank the water showed a trace of sediment, the visibility in looking down into it along the side of an oar being noticeably less. The suspended matter gradually increased toward the west bank for a quarter of a mile. The last third of a mile on the west side held so much sediment that only indistinctly could the bottom of a cup 4 inches deep be seen through it. An oar could not be seen more than 3 or 4 inches below the surface of the water. "At old Fort Wrigley, 140 miles below the Liard, the water on the east side of the river is quite clear, no visible sediment is present, and visibility extends down 3 feet or more. On the west side the bottom of a cup 4 inches deep can be discerned through the water only very indistinctly. The contrast in driftwood also continues striking, being very abundant on the west and scarce on the east side." This contrast, though in a somewhat less marked degree, extended as far as New Fort Wrigley, 160 miles below the Liard, the northern limit of my journey. At Fort Norman a large river brings the clear waters of the Great Bear Lake drainage basin into the east side of the Mackenzie. This large accession of clear water to the east side doubtless results in keeping the eastern half of the Mackenzie comparatively clear to the head of the delta.

Thus we have the curious phenomenon of two rivers, one a clear and one a highly turbid stream, flowing side by side in the same channel without mixing except in a comparatively narrow zone. As a result the deposition of sediment differs markedly in amount and kind on the two sides of the Mackenzie. The islands of alluvial material which occur at various points in the river below the Liard are all confined to the western half of the stream. The abundant supply of drift logs which comes down the Liard furnishes a large amount of drift timber to the west bank of the Mackenzie. Comparatively little of it lands on the east bank.

DESTRUCTIVE AND CONSTRUCTIVE WORK OF THE RIVERS

The Slave River carries vast quantities of sediment into Great Slave Lake. It enters the lake through several narrow channels,

the mouths of the easternmost and westernmost of them being separated by more than ten miles. The lake water in front of the delta is, for some miles out, quite shallow. The submerged margin of the Slave River delta over several square miles is less than a half-foot in depth. This zone is strewn in most places by numberless logs and trees. Inside these comes a broad, irregular fringe of grass-covered land with no willows or other trees, too low for the bank to show. Farther up the delta some of the shores have been built up one foot or a little more above the late summer stage of the water and are covered with willows. Between these islands of the delta, with willow and other low trees, stretches a vast network of shoal-water channels and marsh land. Nearly all these hannels are bordered with large quantities of driftwood. Still higher up the delta small poplars are scattered in patches among and behind, or inland from, the willows. Some miles up from the lake, where the banks rise about 3 feet above the water, spruce comes in with poplar. There is, however, no relief beyond the increase of a few inches or eet in the elevation of the shore above water. With this slight elevation cut banks appear, together with the slumping of trees and sections of the bank into the river.

Along the Sawmill branch of the delta willows and alders make a solid wall of low, overhanging brush. The banks under these show great numbers of ogs projecting from the silts, as noted by McConnell.[1]

Above the delta the banks rise to an average height of 7 or 8 feet above the ordinary midsummer stage of the river, and 10 or 15 feet is not unusual. The banks are nearly everywhere of fine silt. The following is a representative section taken several miles above the delta:

Soil and peaty material	1 foot
Silt and dark bands of organic matter in alternating bands	4 feet
Fine gray silt	7 feet

Cut banks are found everywhere on one side or on both sides. These retreat rapidly during the warm season. A trapper's cabin was observed at one point partially undermined by the sapping of

[1] *Canada Geol. Surv., Ann. Rept.*, IV, 1888–89 (1890), p. 66 D.

the river. The spruce timber is found caving into the river along considerable stretches. Where a strong current sets against the bank caving proceeds as rapidly as the face of the cut bank thaws. The heavy mat of moss and vegetable matter prevents thawing downward beyond a couple of feet, or less in most sections. The lateral thawing on the face of cut banks results in overhanging masses of silt covered with forest trees (Fig. 3). These finally break off from the bank as thawing and undercutting proceeds, and the slumping frequently splits the trunks of trees, leaving half of

FIG. 3.—Destructive river work on the outside of a curve, lower Slave River

stump on shore. Islands are formed quickly, and many of them disappear quickly. A sandbar first appears; then a multitude of willows spring up. If ice and floods are not too devastating during the next seasons, the small willows persist and materially aid in adding more sediment to the bar.

The building of silt islands below places of maximum cutting, or opposite cut banks on the inside of the curve which results from their development, is seen throughout the course of the Slave River below Fort Smith. These islands, if near one bank, are likely to have successive zones of sediment added to them on the side next the channel with the lesser current, until it is closed and they become

a part of the mainland. All stages of these islands may be observed, from the sandbar just emerging from the water, with no trace of vegetation, to the island with a mature forest of large spruce. As soon as a bar island is built sufficiently above low-water stages for any vegetation to survive on it, a dense growth of willows covers it. These for some years practically exclude other kinds of trees. Their enormously long roots form a network which protects the loose silty material of the young island from destruction by high water, while their twigs and stems greatly accelerate the accumulation of sediment by checking the velocity of the current around

FIG. 4.—Constructive river work on the inside of a curve. Note three successive growths of willows in front of the tall spruce timber representing periodic increments of silt bands to the river bank.

them. The growth of the silt island is therefore rapid after the first growth of willows has become well established. When the island has been built sufficiently high by the annual accretion of sediment, poplars and later spruce begin to displace the willows. Frequently three or more zones may be distinguished around these islands, each a year or more younger than the one inside it, by the height of the willows on them (Fig. 4).

Above the mouth of Slave River for about 125 miles cut banks of yellow sand 15 to 18 feet high are common for long stretches. They terminate abruptly against the ordinary alluvial banks and evidently represent a different and earlier set of deposits which probably are of lacustrine origin. Immediately below the Grand

Detour cut banks of this yellowish sand and gravel 40 feet high are exposed.

The outermost island at the west end of the Grand Detour illustrates the lateral migration of islands which is sometimes observed. The western border is a recent sandbar formed during the present year. Inside this border is a crescent of willows one year old, while the third zone is a very narrow belt of willows nearly mature. The eastern and oldest part of the island is covered with poplars. This east side, however, is a cut bank and is being removed apparently at the same rate at which the western shore is being built up. On the north half of the Grand Detour the cutting is all on the outside bank, but this is not true of the south half, where islands in the channel deflect the current to the inside of the bow, where it now appears to be doing the maximum amount of cutting in beds of buff sand toward the upper end of the bow.

Near Fort Smith the sandbanks of the river reach their maximum height. At the steamer landing at Fort Smith the top of the bluff is 125 feet above the level of the late-summer stage of the water. The base of the section is a bed of thinly laminated gray clay 6 feet thick with numerous concretions which have the appearance of being built up of a series of disks each smaller than the preceding. Above this laminated clay the beds appear to be composed entirely of sand.

For 16 miles above Fort Smith the Slave River flows over a series of granite ledges and between numerous low, rounded, granite islands which interrupt navigation. Above this series of rapids most of the islands are composed either partially or exclusively of granite or limestone instead of silts as in the lower Slave. Above the Stony Islands, where the granite islands rise to a maximum of more than 100 feet above the river, numerous low, granite bosses also rise at intervals a few feet above the water surface, in many cases only a foot or two above low-water stage. Some of them are only 10 to 20 feet in length. Groups of half a dozen or more of these small granite islands are seen in a distance of 200 yards up and down stream. These granite knobs are the nuclei of the many long alluvial islands seen in this part of the river. Frequently a pile of driftwood caps the top of one of the low granite knobs

(Fig. 5). Such a drift pile checks the current and furnishes the beginning of the conditions essential to island formation. The river makes a deposit of silt below it, and this, in time, may connect with another similarly formed island by downstream growth. These low knobs prevail up to the mouth of the main outlet of the Peace. Above the mouth of the Peace the knobs of granite increase in elevation till 25 feet is an average height. Still higher up the Slave River the granite knobs increase in height toward Little Lake and Lake Athabasca, just north, until an elevation of 150 feet or more is reached. In Peace River the same type of island construction and destruction which characterizes the lower Slave is seen.

FIG. 5.—Island composed of drift timber, Slave River

Great numbers of spruce trees are being undermined constantly and thrown into the river. This timber from the cut banks of the Peace and Slave is the source of the enormous quantities of drift logs which line the shores of Great Slave Lake (Fig. 3). Some of the logs accumulate on the low, granite-island knobs and form islands, some of which appear, at high water, to consist exclusively of logs (Fig. 5). Trees whose roots are heavily loaded with earth and stones often strand in shoal water and form the nuclei of new islands.

The delta of Athabasca River near the western end of Athabasca Lake is very similar to that of Slave River in Great Slave Lake. The lake water in front of it is only 2 to 4 feet deep for a considerable distance except along a narrow, crooked channel. The banks rise above the river (late-summer stage) less than 1 foot for 3 or 4 miles. Higher up from the lake they rise gradually to about 3

feet, when willows become common. Ten miles above the river mouth the banks rise to 5 or 6 feet, and large willows and alders are common, but no spruce trees or other evergreens are seen. The banks of alluvium increase gradually in height till at the old Fort Forks at the head of the delta they rise 10 or 12 feet above low water.

Numerous good examples occur in the lower part of the Athabasca, in the cut banks, of tree stumps which have been buried where they grew under from 2 to 6 feet of alluvium by the shifting of the course of the river. They are illustrated by one of E. T. Seaton's figures.[1] O'Neill[2] has described similar examples of alluvium-buried forest beds in the delta of the Mackenzie where the buried stumps are much larger in girth than any other trees now growing in the delta. The testimony of the land surveyors who have run their lines across an extensive region between the lower Peace and Athabasca rivers indicates that with the exception of two or three localities bedrock outcrops are wanting over a vast area between these two rivers, an area which is doubtless underlain throughout by fluvial and lacustrine deposits.

About 15 miles above the Old Fort forks the river cuts into a sand bluff 75 or 80 feet high. The heavy load of sand acquired by the river at this and other points higher up results in extensive sandbars which are spread over the middle of the river and interfere with steamer navigation at low water. About 3 miles below Point Brule the extensive alluvial and lacustrine deposits are terminated on the east side of the river by land rising 200 feet or more above it.

CONTRASTING FEATURES OF THE MACKENZIE RIVER

The bowlder pavements are among the most striking features of the Mackenzie River. These marvelous pavements, resembling cobblestone roadways, often stretch along both banks of the great river without interruption for miles (Fig. 6). They frequently extend up the concave banks from below low water to a height of 25 feet or more above it. The shores of many of the islands as well as the banks of the river are paved with bowlders. On the Slave, lower Peace, and lower Athabasca rivers the pavements are entirely

[1] *The Arctic Prairies*, p. 197. Charles Scribner's Sons (1911).

[2] *Canada Geol. Surv., Sum. Rept.* (1915), p. 239.

absent. The channels of these streams are cut in lake and river silts which contain no bowlders, while the channel of the upper Mackenzie is cut for the most part in glacial till containing an abundance of bowlders, which through the grinding and sliding of the ice during the spring break-up are pressed deeply into the clay and built into pavements.

The contrast between the bowlder-paved banks of the Mackenzie and the bowlder-free banks of the rivers just mentioned is related to another feature in which the Mackenzie contrasts sharply with these rivers in the bowlder-free silts. The latter meander widely, while the former pursues a fairly direct course, its bends showing none of the characteristics of typical meandering streams.

FIG. 6.—Bowlder pavement on island opposite Old Fort Wrigley, Mackenzie River.

The Grand Detour on the lower Slave is an example of the meanders of this stream and the lower Peace. At the Grand Detour the Slave swings abruptly to the westward in a great loop of about 20 miles. The distance across the base of this meander is only one mile. The relatively direct course of the Mackenzie as compared with the meandering lower Slave and Peace rivers can be explained, in part at least, by the protection which the bowlder pavements afford against lateral cutting. These pavements furnish protection against erosion of the banks as effective as artificial riprap, and thus prevent the excessive cutting at the bends which in many streams leads to the formation of loops and oxbows.

The plowing and gouging action of ice is nearly everywhere in evidence along the Mackenzie. At the head of the river, in the shallow eastern channel, one can see through the clear water numerous deep grooves made by ice cakes or bowlders pushed by ice in the bowlder clay of the bottom. In the gravel or silts of low islands the broad grooves made by ice-shoved bowlders or ice blocks can often be traced for a considerable distance (Fig. 7). In some localities the plowing and scooping action of the ice carries large quantities of mud from the bottom to the banks of the river (Fig. 8).

FIG. 7.—Trail left by ice-shoved bowlder or ice cake. Note the cratic course unlike that left by drifted tree roots, Mackenzie River.

The upstream ends of some of the low islands are built up in this way several feet higher than the rest of the island. In such cases the ice is likely to build a clay dike across the head of the island at right angles to the course of the river terminating at the top in a sharp ridge. The front of such a dike is frequently bowlder-paved and thus becomes almost as resistant to river erosion as a hard rock cliff (Fig. 9).

A feature of the ice work along the banks of the Mackenzie is the distribution of great numbers of a small bivalve, *Sphaerium vermontanum*, over the higher levels of the bank, much higher than the ordinary stages of the river in summer could carry them. I

have never seen this shell in the shallow water of the river, although other shells are common there. It appears, therefore, that it lives

FIG. 8.—River bottom clay and silt shoved on bank of an island by ice scour, Mackenzie River.

abundantly in the deeper parts of the river and reaches the localities where found on the banks as a result of ice excavation and the vagaries of strong current action and transportation during the

FIG. 9.—A clay island protected from erosion by a bowlder pavement

spring break-up. When the ice breaks on the river in the spring, ice jams occur which raise the river to abnormal heights at various localities. McConnell[1] has given the following striking descrip-

[1] *Geol. Surv. of Canada, Ann. Rept.*, IV, 1888–89 (1890), p. 87 D.

tion of this phenomenon as observed by him at the mouth of the Liard:

> Huge cakes of ice under the enormous pressure were constantly raising themselves on end and falling, and the whole mass, urged forward by the terrible energy of the piled-up waters behind, was battering a way across the Mackenzie. The ice of the latter, fully five feet thick and firm and solid as in midwinter, was cut through like cardboard, and in a few moments two lanes were formed across its entire width, while a third was open for some distance below, before the force of the rush was exhausted and the movement ceased. In the afternoon the crashing of trees in a channel behind the island, concealed from view by the intervening forest, was distinctly heard and showed that a temporary vent had been found there, and in front of the fort intermittent fountains played at intervals from holes and crevices in the ice. At midnight

FIG. 10.—A remnant of a mass of river-shoved ice and the bowlder pavement which such ice levels and smoothes, Mackenzie River 15 miles above Fort Wrigley.

> the dam at the mouth of the Liard gave way and the massive crystal structure was hurled by the liquid energy behind it against the firm ice in front with such force that the whole sheet, for some miles below the fort, was crushed into fragments by the impetuosity of the assault.

At the Ramparts ice jams are reported to have sometimes raised the river nearly 100 feet.

About 15 miles above Fort Wrigley, I observed the remnants of one of these ice jams—an accumulation of great ice blocks which had remained unmelted as late as July 22 (Fig. 10). At this date the principal mass of ice blocks had a thickness of 25 feet. They were covered with a thin veneer of dark mud, and hundreds of specimens of *Sphaerium vermontanum* were scattered over their surface.

Good examples of rock basins which represent apparently one phase of the work done by river ice occur on the limestone island opposite old Fort Wrigley. A considerable area of limestone beds lying approximately horizontal on the northeastern side of the island is covered by the river during the spring break-up, but exposed through the summer. On this area a group of four rock basins has been developed in the limestone. The rim of the largest of these rises from 5 to 10 feet above the bottom. This basin has a maximum length of 65 feet and a width of 30 feet (Fig. 11). Another of these basins has a diameter of 10 feet and a depth of 5

FIG. 11.—A rock basin in limestone between low and high water, Old Fort Wrigley, Mackenzie River.

feet. The basins appear to be the product of the plucking action of the river ice which covers them during the late winter stages of the river.

LAKE FILLING

Two large lakes, Athabasca and Great Slave, lie in the path of the Mackenzie-Athabasca drainage system. Great Slave Lake, much the larger of the two, has a length of about 290 miles from east to west. A recent survey of part of the north shore by A. E. Cameron, of the Canadian Geological Survey, changes the rank in size of Great Slave Lake from fifth to fourth among the great lakes of the continent. As pointed out by McConnell,[1] it seems originally to have had "the form of a great cross with one arm

[1] *Geol. Surv. of Canada, Ann. Rept.*, IV, 1888–89 (1890), p. 65 D.

penetrating the crystalline schists while two others stretched north and south along the junction of these with the newer sedimentaries, and the fourth extended itself over the flat-lying Devonian to the west." Lake Athabasca lies almost entirely within the limits of the pre-Cambrian rocks.

Inspection of the map (Fig. 1) will show that the drainage of an enormous area in Northwestern Canada, extending from the interior of the Rocky Mountains region far into the pre-Cambrian area west of Hudson Bay, passes through Lake Athabasca and Great Slave Lake. Practically all of the vast quantity of sediment which is annually stripped from this extensive area is left in these great settling basins. A noteworthy feature of this lacustrine sedimentation is the extreme inequality of its distribution. Probably 95 per cent of the immense volume of sediment which enters Great Slave Lake is poured into the south side of the lake. The streams entering the north side of the lake are nearly all small and comparatively insignificant. In the course of a survey of the north shore of the west arm of Great Slave Lake, A. E. Cameron found that "throughout the entire 136 miles of shore line between the Mackenzie River and the north arm only one stream, and it a very minor one, was found entering the lake" (manuscript). The streams which do enter the north shore of the lake lose most of their sediment in passing through small lakes before reaching Great Slave Lake. On the south shore, besides the Slave, which is one of the great sediment-bearing streams of the continent, three other rivers enter, each of which has a considerable volume. These are the Taltson, the Buffalo, and the Hay. It is the zone of lake bottom bordering the 150 miles of the south shore receiving these streams which takes the great bulk of the river-borne sediment. Great Slave Lake opposite the mouth of Slave River, which carries the great bulk of the silts entering the lake, has a width of more than 60 miles. Little or none of the sediment brought in by the Slave has any chance of being deposited in the northern half of the lake. Coastwise currents, however, distribute the silts from the Slave and other south-shore streams widely along the south-shore bottom zone. It is probable that along the shore line between the Hay and the Buffalo rivers the prevailing direction of the coastwise

currents is easterly. This was evidently the case off the mouth of the Buffalo when I passed it early in July. The canoe entered muddy water some distance east of the mouth of the stream, but entered clear water immediately west of the west bank of the river, although a breeze from the northeast was blowing at the time. At a later date Mr. Cameron made similar observations at the mouth of the Buffalo. The muddy water of the Slave ceases to be noticeable in the lake 10 or 12 miles west of the western side of the delta.

There is probably no lake in North America which receives anything like the amount of driftwood which is poured into Great Slave Lake, chiefly through the Slave River (Fig. 12). The shores

FIG. 12.—Drift timber on the shore of Great Slave Lake

are nearly everywhere lined with enormous quantities of logs, many of which came from a thousand miles or more up the Peace. Large quantities of this driftwood must eventually become water-logged and sink. Practically none of it leaves the lake by the Mackenzie. At some localities the drift timber is intimately mixed with the shingle of the beaches (Fig. 13).

In Lake Athabasca sedimentation appears to be even more localized than in Great Slave Lake. The maximum length of Lake Athabasca, which nearly equals that of Lake Ontario, lies in an east and west direction. The great bulk of the sediment which the lake receives is poured into the western end by the Athabasca and Peace rivers. It is discharged from this end by way of Little Lake and Slave River. The relationship of the Peace River discharge to Lake Athabasca is peculiar and variable. Three or four

outlet channels of the Peace empty directly into Slave River, but the Quatre Fourches channel, which branches off above the Slave River outlets, empties into Lake Athabasca. Ordinarily by far the greater part of the Peace River water flows directly to Slave Lake via Slave River; but a conjunction of low water in Lake Athabasca and high water in the Peace River may for a time reverse the direction of flow in the upper Slave River and turn all of the Peace River outflow into Lake Athabasca. Such a reversal of drainage involves the temporary obliteration and reversal of Little Rapid, located about 25 miles north of Lake Athabasca in Slave River. Father Lafebre, of the Catholic Mission, informs me

FIG. 13.—A double beach of shingle and drift wood, shore of Great Slave Lake

that he has observed this reversal in May. It thus appears that at times the whole of the combined volume of sediment carried by the Peace and the Athabasca is dumped into Lake Athabasca. When this reversal of current near the head of the Slave River occurs, it is evident that the deposition of sediments must proceed in the western part of Lake Athabasca at an enormously increased rate. Under these special conditions the whole of the Peace River sediment, nearly all of which ordinarily reaches Great Slave Lake, stops in Lake Athabasca. During the unusual seasons when the Peace River contributes largely to the Lake Athabasca sediments, the annual layers of silt would not only be thicker than those ordinarily laid down but would also probably have a much greater easterly extension.

Lakes Mamawa and Clair, lying west of Athabasca Lake, appear to represent parts of a former greater Lake Athabasca which have been segregated into separate lakes by lake filling. Lake Clair has a shore line approximating 200 miles in length. Its depth is reported seldom to exceed 8 feet. Little Lake, through which the outflow of Lake Athabasca passes, is extremely shallow except for a channel through which most of the outflow passes to Slave River. East of this channel a large area on the north side of the lake is completely silted up. On the west side large areas of aquatic plants and stranded logs indicate the approach of the final stage and extinction of the lake.

Observations made on the relative clarity of the Slave River water above and below the mouths of the Peace show but a slight difference in the clarity of the water. This would indicate that the river water passes through the narrow western part of Lake Athabasca too quickly to lose nearly all of its sediment.

NOTES ON THE MISSISSIPPIAN CHERT OF THE ST. LOUIS AREA

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The origin of chert is a question which is still open to discussion. Although several of the chert series of Europe have been studied somewhat in detail by a number of geologists,[1] among the more important Hull and Hardman, Hinde, Sollas, Renard, and Cayeux, the conclusions reached with regard to the origin of chert have been considerably at variance. In this country Lawson and Palache seem to have demonstrated the organic (radiolarian) origin of certain Californian cherts. The Missouri cherts, chiefly Mississippian, and some of the closely associated cherts of neighboring states have been studied, although not in detail, by Shepard, Ball and Smith, and Van Tuyl, and, in thin section only, by Hovey. The conclusions as to the origin of the chert have not been in agreement. The present paper presents the results of a detailed study of the Mississippian cherts of the St. Louis area both in the field and in thin sections.

OCCURRENCE OF THE MISSISSIPPIAN CHERT OF THE ST. LOUIS AREA

The Mississippian chert of the St. Louis area is found in the St. Louis and in the Burlington-Keokuk limestones, to a slight extent in the Warsaw shales, and in very rare, small patches in the

[1] E. Hull and E. T. Hardman, *Trans. Royal Soc., Dublin*, I (1878), 71. G. J. Hinde, *Geol. Mag.* (III), IV (1887), 435–46. W. J. Sollas, *Am. Mag. Nat. Hist.* (5), VI (1880); VII (1881); *Proc. Roy. Soc., Dublin*, VI (1887), Part 11. A. F. Renard, *Bull. Acad. Roy. Belgique* (2), XLVI (1878), 471. L. Cayeux, *Ass. franç. pour l'avanc. de Sci.* (Carthage, 1906), pp. 220–93. A. C. Lawson and C. Palache, *Bull. Geol. Dept. U. of Cal.*, II (1902), 354–65. E. M. Shepard, *U.S. Geol. Surv., W.S. Paper 195* (1907), p. 19. T. M. Van Tuyl, *Proc. Iowa Acad. of Sci.*, XIX (1912), 173–74. E. O. Hovey, *Mo. Geol. Surv.*, VII, Part II (1894), pp. 727–39.

Salem limestone. The stratigraphic position of the chert beds is shown in the accompanying generalized section of the St. Louis area (Fig. 1). The Burlington-Keokuk limestone wherever exposed

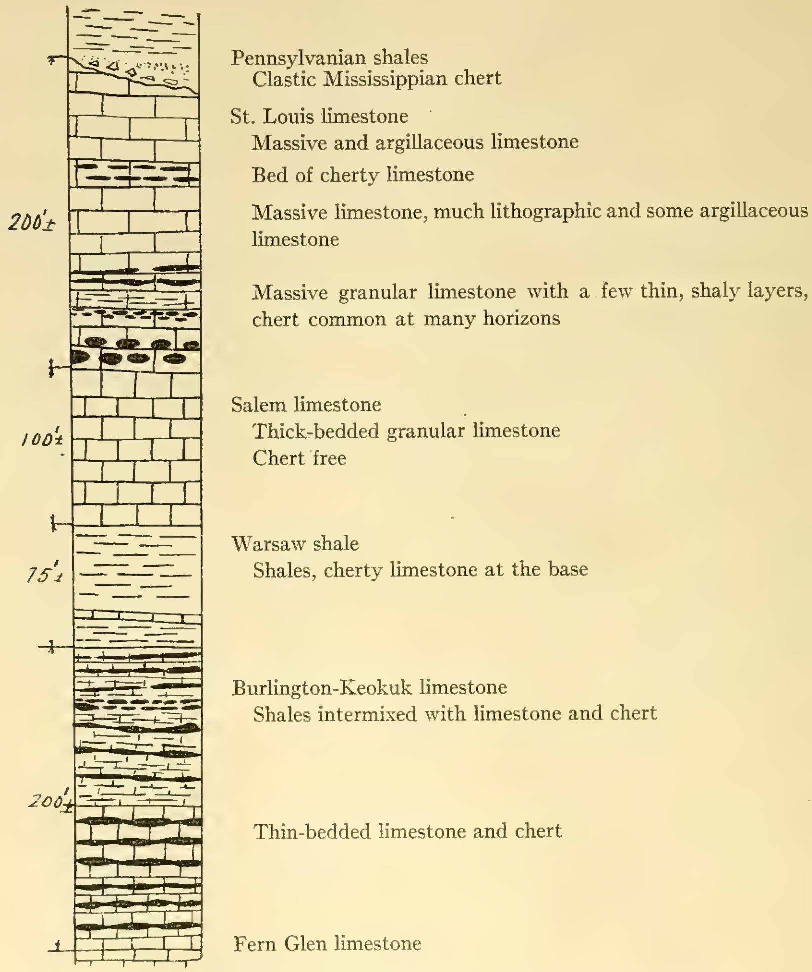

FIG. 1.—Generalized section of the St. Louis region

in this area is consistently very cherty. The amount of chert in the St. Louis limestone varies considerably from place to place. The presence of more or less chert at the base is characteristic, but it

was impossible to correlate with certainty throughout the area the higher cherty horizons.

MORPHOLOGY OF THE CHERT BEDS

The general form of the chert varies considerably from bed to bed, although it seems to be more or less constant for any individual horizon. It is possible to distinguish several distinct types of occurrence of the chert. Most of the chert in the Burlington-Keokuk limestone and some of the chert in the St. Louis limestone are in nodular bands or bands of flattened nodules. The nodules are irregularly elliptical with horizontal diameters subequal and one and a half to twice the vertical diameter, and are seldom less than three centimeters or more than ten centimeters in diameter vertically. The nodules are rounded and usually sharply delimited, at least to megascopic examination, from the inclosing limestone. In any given chert bed these nodules show distinct distribution parallel to the stratification and by coalescence form the nodular bands intercalated between the thin limestone beds. In a few chert beds in the Burlington-Keokuk the chert is irregularly ramifying, with angular outlines, and in general pattern resembles some of the mottled Ordovician limestones. Although the chert of this type usually crosses many distinct layers of the limestone, the greatest development shows distinct distribution parallel to the stratification. A form of the chert very characteristic of the St. Louis limestone and found but very rarely in the Burlington-Keokuk are the bands of nodules, spherical or ovoid in shape and six to sixty centimeters in diameter. The contact of the nodule and the limestone is apparently sharp, but there is usually present a thin chalky-looking transition zone. The nodules in a given band characteristically are well aligned to some horizon, in many cases the middle of a thick limestone bed. A form of the chert that is found both in the St. Louis limestone and in the Burlington-Keokuk limestone is a thin band, pancake-like in the St. Louis and platelike in the Burlington-Keokuk. These bands most commonly are six to ten centimeters thick, but in some cases much more, and fifteen to fifty meters long. The contact of the chert of these bands with the limestone seems to be sharp.

LITHOLOGICAL CHARACTER OF THE CHERT

To the naked eye the chert characteristically appears stony, but in some cases granular or chalky, although in the latter cases the chert is not appreciably less tough or hard. In color the chert varies from dirty white to dark gray and, except for one thin band of chalcedonic chert, is mottled and banded. The mottling is similar in effect to that given by the grain to the limestone and is apparently a pseudomorphic character of the chert reflecting the granular character of the limestone. The banding is concentric with the form of the nodule, or horizontal. In the latter case it is a retention of the stratification markings. The chert with rare exceptions is fossiliferous wherever the limestone of that horizon is fossiliferous. Crinoid stems are by far the most common fossil. Bryozoa, Spiriferi, Producti, and other brachiopods, Lithostrotion in the St. Louis limestone and Fusulina are also common. A notable feature about the fossils is that in a very great number of cases they are still calcareous and do not show the effects of the siliceous replacements of the rest of the rock.

In thin section under the microscope the chert is seen to be composed chiefly of quartz with more or less calcite, and in some cases with chalcedony, opal, dolomite, pyrite, and iron staining. The quartz making up the mass of the chert is in excessively fine grains, less than 0.01 mm. in diameter, which are not clearly distinguished even under the high power, and it is to the compensation due to the superposition of these small grains that many of the areas dark under crossed nicols are to be attributed. Locally, in many cases within a shell, there are patches of allotromorphic grains of larger size (0.1 mm.). In a few thin sections there were seen larger, subangular, clastic grains. The calcite, abundant through much of the chert, is in small rounded grains that cloud certain areas or form patchy aggregates through the chert, or is in large grains forming the unreplaced shells. The calcedony, when present, is in thin, fibrous, wavy bands that permeate part of the chert, lining shells, and microscopic cavities. The presence of the opal is inferred from the presence in part of the chert of much isotropic material with a moderately low index of refraction. The dolomite, where observed, was in small rhombs scattered through the chert and was distinctly

more abundant in the chert than in the surrounding limestone. Pyrite was present in only a few cases and was in small cubes in the center of quartz-filled cavities. In much of the chert there is a slight amount of iron staining present.

The structure of the chert as revealed under the microscope varies considerably. Part of the chert is massively composed of very fine grains, whose boundaries cannot be made out. Much of the chert is similarly composed in large part, with ramifying, banded microscopic masses of calcedonic material or interlocking quartz grains, which seemed to have filled pre-existing cavities. The interior cavities of shells are in most cases filled with interlocking quartz grains. The shells, even very minute ones, for the most part are composed of calcite in medium-sized grains, but in some cases show partial or complete replacement. Where replacement of a shell has taken place it is mostly by fine allotriomorphic quartz granules. Concentric banding is shown by much of the chert and is caused in some cases by very slight differences in the amount of staining, probably ferruginous, and in other cases by a variation in the amount of admixed calcite grains, the calcite rich areas tending to a chalky white color. In a chert much resembling in marking the mottled Ordovician limestones the mottling is likewise due to a rapid variation of the proportions of calcite to quartz grains. Banding due to stratification is present in some of the chert and is shown by the orientation of minute shells, by variation in the amounts of a cloud of fine black specks, and by variation in the staining.

RELATION OF CHERT TO SURROUNDING LIMESTONE

The character of the contact of the chert and the limestone apparently varies with the different chert beds. In many cases there is a visible transition extending over a zone of one to two centimeters. This is particularly the case with the spherical nodules of the St. Louis (Fig. 2). But the contact more commonly is sharp, at least under megascopic examination. In the Osage chert of Iowa such contacts are reported by Van Tuyl microscopically to show gradual transition. In the thin sections of St. Louis

chert examined the transition was distinctly sharp, being confined to a zone of 0.2 to 0.4 millemeters in width.

The lateral contacts of the larger, semispherical nodules can be seen in many cases to be zones of slight displacement. The lines of stratification running into or across the chert are broken and slightly displaced upward, the more so toward the top of the nodule, and not at all or only faintly in reverse at the base. The ends of the line of stratification in the adjoining limestone in many cases

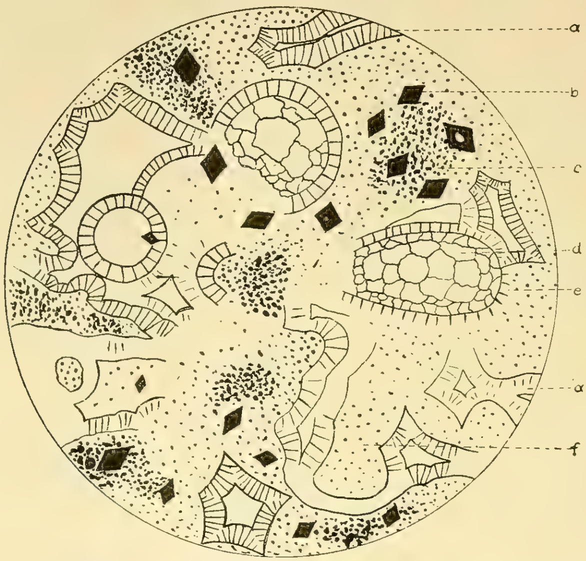

FIG. 2.—Chert from the St. Louis limestone, St. Louis, Missouri, under the high power: *a*, chalcedony; *b*, dolomite rhombs; *c*, limonite stain; *d*, granular quartz; *e*, silicified shell; *f*, microgranular groundmass.

are bent up near the nodule with the upper ones arching over, but in other cases run to the contact without deviation. Slickensides were found in a very few cases on the lateral contacts, showing relative movement upward of the chert of the nodule.

CHARACTER OF THE ROCK INCLOSING THE CHERT

Although chert is confined to calcareous rocks, the exact character of the rock in which chert appears varies widely. The grain seems to have no effect on the presence of chert, which is found

indifferently in fine-grained, even lithographic limestones, and in coarse-grained ones. It is found in massively bedded as well as in thin-bedded limestones. It is not found, to the writer's knowledge, in pure or only slightly calcareous sandstones or shales, but is found in arenaceous and argillaceous limestones. It is found in highly magnesium limestones and in very pure limestones. A series of analyses of the chert-bearing St. Louis and Burlington-Keokuk limestones at St. Louis show a variation in composition as given in Table I.

TABLE I*

Limestone	Insoluble Siliceous Residue	Combined Oxides	$CaCO_3$	$MgCO_3$
St. Louis.............	1.48–9.56	0.35–1.82	61.88–94.97	0.94–24.53
Burlington-Keokuk....	1.10–4.35	0.40–1.82	77.95–94.50	3.18–14.84

*Analyses by A. E. Atwood, *Geol. Surv. of Missouri, Bull. No. 3* (1890), p. 77.

CONTEMPORANEOUS CHERT OF OTHER AREAS

In areal distribution these Mississippian cherts are not restricted to the St. Louis area, but are widespread and are characteristic of the St. Louis limestone and equivalent formations and the Burlington-Keokuk limestone and equivalent formations practically wherever they are found. The Salem limestone of the St. Louis area is free from chert, as is also the Bedford oölite, its equivalent to the east. The exact extent of the distribution of the chert in the St. Louis limestone and the Burlington-Keokuk limestone is best shown graphically in Figs. 3 and 4, on which are plotted the outcrops of these formations and the areas in which they are chert-bearing. The correlation of formations on these maps is taken largely from B. Willis' "Index to the Stratigraphy of North America," *U.S. Geol. Surv. Prof. Paper 71*. While the morphology of these equivalent chert beds varies somewhat from locality to locality, yet there seems to be a greater or smaller constancy of habits of the chert of each formation. The St. Louis is characterized by even, ball-like chert even to Alabama, while the Lauderdale is spoken of as platelike, and the Boone chert and Grand Falls chert of western Missouri are said to be lenslike or sheetlike. It is perhaps worthy

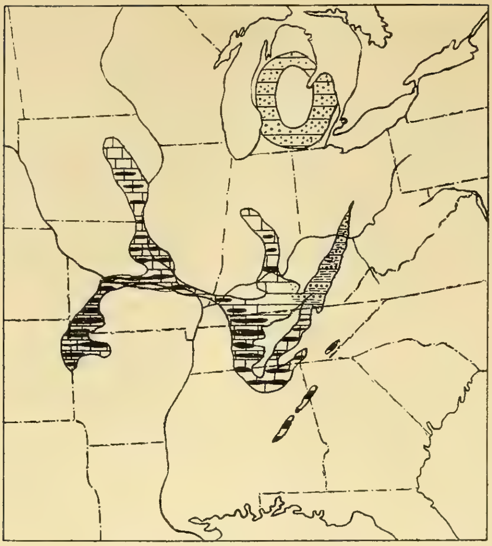

FIG. 3.—Distribution of the chert in the Burlington-Keokuk limestone and equivalent formations.

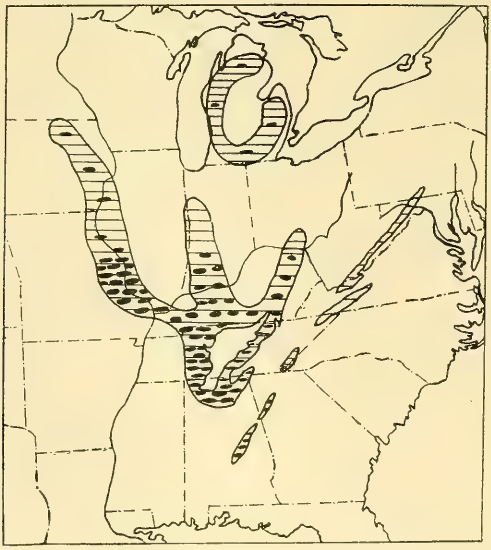

FIG. 4.—Distribution of the chert in the St. Louis limestone and equivalent formations.

of note, although very possibly nothing more than a coincidence, that much chert is found in the lower Carboniferous limestones of England, Ireland, and Belgium.

AGE OF CHERT

In age the chert of the Mississippian of the St. Louis seems without doubt to lie between the early Pennsylvanian and the time of formation of the chert-bearing limestones. The evidence of the pre-Pennsylvanian age of the chert lies in the presence of the Mississippian chert as clastic fragments in the base of the Pennsylvanian. In a Missouri-Pacific railroad cut between Kirkwood and Barrett's Station, St. Louis County, Missouri, and also in a Frisco railroad cut a half-mile east of Meramec Highlands, clastic chert carrying Lithostrotion proliferens and Spirifer Keokuk and showing predepositional weathering is to be found in abundance at the base of the Pennsylvanian shales. In Miller County, Missouri, clastic chert from the Burlington limestone is reported as being present in the Graydon sandstones and the Coal Measures shales. In the Joplin district likewise clastic Burlington chert is reported as lying at the base of the Pennsylvanian.

The evidences of the formation of the chert later than the formation of the containing limestone are several. The replacement of fossils has been cited and probably in some cases correctly so. Although the fossils in the great number of cases have not been replaced, the replacement of the fossils, especially the larger ones, when studied in their sections under a microscope seems, partly at least, surely to have taken place after the formation of the chert. The retention in the chert of the markings of the limestone, including the grain, stratification, styolithes, and fossiliferous character, is valid evidence of the secondary character of the chert. The mottling of the chert in very many cases accurately reproduces the appearance of the granular character of the limestone. The stratification markings and the variation in grain and fossil content in the different layers can in many cases be traced into or across the chert. The arching of the stratification and the faulting and slickensiding at the contacts of the nodules are also evidences of the secondary character of the chert. The stratification of the limestone in which

the pancake-like chert bands appear, for example, is more or less contorted, although in the closely associated, chert-free beds it is even and regular. The slight vertical displacement in the slickensides that are found at the lateral contacts of some of the larger nodules has already been mentioned.

Yet while the chert seems definitely to be secondary, there is an aspect on its part of contemporaneity with the limestone. This is evidenced by the widespread development of the chert in the St. Louis limestone and in the Burlington-Keokuk limestone, although the intervening Salem limestone—Bedford oölite limestone—is practically chert-free. The constancy of habit of the chert in the St. Louis limestone and in the Burlington-Keokuk, respectively, over a wide area has already been noted. The development of the chert also is parallel to the stratification. In a band of isolated nodules there is characteristically a striking alignment of the nodules at some level in a bed, often a massive one. There are in some cases several bands, and in a few cases there is no alignment of the nodules, but where the bands are present they are parallel to the stratification. The nodule-containing bed is in some cases three or four feet thick, with no shale partings, is uniform in grain and character throughout, and shows no apparent cause for percolating waters, whether silica-bearing or not, to flow at certain definite and localized levels. The pancake-like chert masses and the chert lenses likewise show conformity to stratification, although in this latter case there is in many places coalescence of several lenses by lateral thickening. As far as could be seen there was no possibility of localization of the chert at definite levels by control of percolating waters by shale partings or such. If the chert were purely epigenetic, it would seem probable that the chert bands would show some tendency to cut across the stratification.

The various theories that have been proposed to explain the origin of chert may be said in essence to be six.

I. The silica is of organic origin, derived chiefly from the spicules of siliceous sponges. The silica may be derived from other of the siliceous organisms, as, for instance, in the case of the radiolarian cherts of California.

1. The chert is supposed to be derived from colloidal silica which formed from the decomposition of siliceous sponges and collected in the depressions of the sea floor. The chert bands are supposed to represent former sponge beds, where the sponge remained accumulated in place over a considerable area.

2. The chert is supposed to form before consolidation of the limestone through the solution of scattered siliceous spicules and the almost immediate replacement of parts of the limestone.

3. The chert is supposed to form after the consolidation of the limestone through the solution by percolating waters of the siliceous spicules and the replacement of part of the limestone by this dissolved silica.

II. The silica is supposed to be of inorganic origin.

4. The chert is supposed to form by the precipitation of silica and the replacement of the limestone in the presence of circulating waters which have passed through sandstones, arenaceous rocks, or rocks containing silicates.

5. The chert is supposed to result from the reaction of the dissolved silica of sea-water with the limestones, with the consequent precipitation of the silica and with possibly a later concentration.

6. The chert results from the diffusion of silica in solution through a limestone. The concentration will vary in the direction of the diffusion, and the deposition resulting when the concentration is sufficient will be in zones perpendicular to the direction of diffusion. As the conditions for diffusion are more favorable in the early days of the consolidation and as the most likely direction for the diffusion is upward toward the surface or downward from it, the deposition will be parallel to the stratification, although independent of it. The development of the chert in successive zones is due to the lowering of the concentration immediately around the first started zone or zones of crystalizing material. The silica may be derived from organic or inorganic sources.

ORIGIN OF THE CHERT OF THE ST. LOUIS AREA

The source of the silica of the chert of the St. Louis area is not as clear as in the cases of the English cherts and flints, the radiolarian cherts of California, and the cretaceous cherts of Texas, and

apparently must remain a matter of conjecture. Evidence of an organic origin is wanting. In slides of the St. Louis chert spicules were present only in one case. In his study of slides of the Missouri cherts Hovey reports that he found only one carrying sponge spicules. Likewise Van Tuyl in his study of the cherts of the Osage series found sponge spicules present in only one sample. Of the presence in numbers in the Mississippian seas of other silica-secreting organisms nothing is known.

In the case of the cherts of the St. Louis area the theory that the chert is formed from the collection of colloidal silica on the sea floor is not applicable, since the chert is plainly secondary. Hinde's application of this theory to explain the presence of unsilicified shells in the chert is not necessary, as the differential replacement is readily accounted for by the lower solubility of the shell material. In this connection a brief series of tests was run on the relative solubility of recent and fossil pelecypod shells, fossil brachiopod shells, on crinoid stems, and on chert-bearing and chert-free limestone. The material was powdered to pass through a two-hundred-mesh sieve and was digested in 25 cubic centimeters one-half normal HCl, plus 350 cubic centimeters distilled water, and the time required for neutralization, as shown by methol orange, was noted. A marked tendency was shown toward less solubility on the part of the shells, crinoidal limestone, and chert-free limestones, such as the Salem, and greater solubility on the part of the limestones associated with chert. The experiments were not extended enough to be conclusive.

That the chert was formed before the consolidation of the limestone from silica derived from the solution of siliceous spicules or tests is possible in the case of some of the chert. But it is definitely not possible in the case of most of the chert, as the chert did not form until after the limestone had acquired its granular character. The formation of the chert in a similar manner during, or later than, the consolidation is more possible. The chert is secondary and is pre-Pennsylvanian, and therefore must have formed during, or not long after, the consolidation of the limestone. There is, however, no positive evidence of the organic origin of the silica. The suggestion that the silica of the chert is exotic and that it has

been introduced from other siliceous formations by the underground circulation, possibly that of the geologic present, does not seem valid. The formation of the chert cannot have taken place through the agency of the present-day circulation, since the presence of the chert at the base of the Pennsylvanian shows the period of formation to have been late Mississippian or early Pennsylvanian. The jasperoid of the Joplin district, furthermore, is a chertlike siliceous deposit that is said to have been deposited by the same underground circulation that is responsible for the mineralization of the region. But the jasperoid is later than the chert and distinctly different. The more serious objection, however, is the conformity of the chert with the stratification. Vertical zones following the joints are not found. The chert is found widespread, but is not found in an adjacent formation and is more or less similar over wide areas, but different in aspect in the different formations.

The derivation of the silica of the chert through precipitation from sea-water is a possibility. Silica is precipitated from solution by calcite and replaces it when H_2CO_3 is present, and, as the accumulating sediments of the ocean bottom usually contain decaying organic matter, H_2CO_3 should be present. A tenth of the yearly increment of saline material in the ocean is silica, but the silica content of sea-water is practically nil, 1 part in 220 to 460 thousand. The very considerable annual increment of silica must therefore be removed quickly, either by direct chemical precipitation or through the action of organic agents. In the case of the Mississippian beds of the St. Louis area it is not known that siliceous organisms were present to any important extent at the place and time of the deposition of the beds. The degree of concentration of the silica in the ocean-water, in connection with the slow rate of diffusion and proximity or distance from the mouth of a river, may be an important factor, contributing to the lack of chert in some limestones, as, for instance, the Salem and Kemmswick limestones. Such chert-free limestones may have formed at a distance from the mouths of rivers, and the silica may have been completely precipitated before currents brought these waters to the place of deposition of these beds.

The principles of diffusion as given by Liebesang and Cole in connection with the origin of flint partially explain some of the features of the chert of the St. Louis area. These principles seemingly explain the formation of the chert after, but not long after, the formation of the limestone—the position of the chert parallel to the stratification but independent of it, the rhythmic deposition of the chert, and the excessive development of the chert within a few hundred feet of a great uncomformity. They are equally applicable whether the silica is derived from organic or inorganic sources, and would seem to necessitate a rather general distribution at the start of siliceous material through the mass. The particular localization at a given horizon of a chert bed might be affected, however, through the influence of a local excess of siliceous material on the concentration at that horizon. The localization might also be affected by the solubility of the limestone of the various horizons. A serious difficulty that would seem to arise in connection with the application of these principles in the present case is the presence of the numerous argillaceous beds. It is difficult to see how much diffusion could take place through these shale beds, and the diffusion would seem necessarily to be confined chiefly to lateral diffusion through the more porous beds.

Editorial

GROVE KARL GILBERT

The passing of Dr. Gilbert after almost seventy-five years of activity deprives geological science of one of its ablest and most honored representatives. It is permitted to few men to leave an equally enviable record. To an unusual degree his work was distinguished by keenness of observation, by depth of penetration, by soundness in induction, and by clarity of exposition. It is doubtful whether the products of any other geologist of our day will escape revision at the hands of future research to a degree equal to the writings of Grove Karl Gilbert. And yet this is not assignable to limitation of field, or to simplicity of phenomena, or to restriction in treatment. The range of his inquiries was wide, his special subjects often embraced intricate phenomena, while his method was acutely analytical and his treatment tended always to bring into declared form the basal principles that underlay the phenomena in hand.

In the literature of our science the laccolith will doubtless always be associated with the name of Gilbert. In its distinctness as a type, in its uniqueness of character, and in the definite place it was given at once by common consent, one may almost fancy a figurative resemblance between the laccolith and its discoverer and expositor. Gilbert's monographs on the Henry Mountains and on Lake Bonneville will long stand as unexcelled models of monographic treatment. His contributions to physiographic evolution, particularly his analysis of the processes that end in base-leveling, link his name with that of Powell, and give to these two close friends a unique place as joint leaders in interpreting morphologic processes. Glacial and hydraulic phenomena were also fields in which Gilbert's powers as an investigator and expositor were signally displayed.

In accuracy of delineation, in clearness of statement, and in grace of diction Gilbert's contributions are certain long to stand

as models of the first order. His personality was of the noblest type; he was a charming companion in the field; he was a trusted counselor in the study. The high place he has held in the esteem of co-workers is quite certain to merge into an even higher permanent place to be accorded him by the mature judgment of the future.

T. C. C.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Sosman, R. B., and Merwin, H. E. "Data on the Intrusion Temperature of the Palisade Diabase," *Jour. Wash. Acad. Sci.*, III (1913), 389–95.

Slabs of the underlying Newark shale and arkosic sandstone have in many cases been "floated" up into the igneous rock of the Palisade diabase of New York and New Jersey, apparently while the latter was still liquid. This paper deals with studies made of the comparative fusion points of the diabase and the arkose. The former begins to melt at 1,150° but does not flow till 1,225°, while most of the latter is fused at 1,150°. The inclusions in the Palisade diabase, however, show no trace of fusion, and the authors conclude that the fusion point of the diabase was lowered by mineralizers at the time of the intrusion.

Spethmann, Hans. *Islands grösster Vulkan. Die Dyngjufjöll mit der Askja.* Leipzig: Veit & Co., 1913. Pp. 143, figs. 36, bibliography.

The author gives first a summary of work previously done in this region, including an account of von Knebel's ill-fated expedition. He then tells of the development of the maps of this region, describes the forms of relief, the climate, and the vegetable and animal life.

The volcano Dyngjufjöll lies east of the central part of Iceland. Its crater, Askja, is the largest in the island, and has a fairly flat bottom of from 55 to 60 square kilometers. In the southeastern portion of this crater bottom is a lake, Knebel Sea, covering about one-fifth of the area, and at its northeast shore is an active crater, Rudloff Crater. Southwest of the lake is a solfatara field. The mountain owes its origin to volcanic eruptions from a conduit within the area of Askja. The material ejected was fragmental, but later was followed by a lava flow which filled the cauldron with a sea of lava and caused overflows at several points. There were various fluctuations of the surface of this flow, the last one being a sinking of the level from 40 to 50 meters. In January and March, 1855, there were eruptions of fragmental materials, and at the same time several large areas of the crater bottom, near the Knebel Sea, settled and filled with water from this lake.

TYRRELL, G. W. "A Petrographical Sketch of the Carrick Hills, Ayrshire," *Trans. Geol. Soc. Glasgow*, XV (1913), 64–83, pls. 2.

Geological description of the upland region on the shore of the Firth of Clyde near Ayr. The hills consist of a series of lava flows of Old Red Sandstone age, and are composed of extrusive andesites and basalts and intrusive dolerites and *plagiophyres*, the latter term applied to plagioclase rocks analogous to the orthoclase-bearing *orthophyres*.

TYRRELL, G. W. "The Petrology of Arran," *Geol. Mag.*, X (1913), 305–9.

Riebeckite-orthophyre or riebeckite-trachyte is described from the Holy Isle, near Arran, and crinanites or olivine-analcite-dolerites, from Whiting Bay and Dippin.

TYRRELL, G. W., FERGUSON, D., and GREGORY, J. W. "The Geology of South Georgia," *Geol. Mag.*, I (1914), 53–64.

A description of the general geology of the island of South Georgia, 900 miles southeast of the Falkland Islands. The only igneous rocks found were certain crystal tuffs of andesitic, latitic, and trachytic character, an intrusive diabase or ophitic gabbro, and a quartz-monzonite-porphyry, the latter a fragment picked up from a moraine.

TYRRELL, G. W. "The Petrology of South Georgia," *Trans. Roy. Soc. Edinburgh*, L (Part iv), No. 25, 1915, 823–36, pl. 1.

This is a detailed petrographic description of the sediments and igneous rocks mentioned in the above paper. The rock previously determined as quartz-monzonite-porphyry is here called granite-porphyry.

USSING, N. V. "Geology of the Country around Julianehaab, Greenland." *Meddelelser om Grönland*, XXXVIII (1911). Pp. 370, figs. 28, maps and secs. 6, pls. 12, chemical analyses.

The southern third of Greenland is extremely poor in sedimentary rocks, only two small areas of post-Archean sediments being found in addition to certain Quaternary loam, sand, and gravel deposits. By a comparison with the sediments of northeast Canada, however, the order of succession of the various rocks may be inferred: Archean gneisses and schists, Algonkian(?) granites, diorites, etc., Devonian plutonic

rocks and volcanic sheets, and Quaternary moraines and alluvium. The most widely distributed rock in this region is a hornblende-bearing biotite-granite. The Devonian sheets are trachydolerites and alkali-trachyte. The later abyssal rocks are granites, syenites, nephelite-syenites, gabbros, and essexites, and of these all but the gabbros and essexites, which form small bosses, occur as batholiths. The nephelite-syenites are represented by lujavrites and other rare types, several of which have been given new names.

Naujaite is a sodalite-syenite, but since the latter term was used for rocks of quite different characters by Steenstrup, Lindgren, and Hibsch, the new name is proposed for a nephelite-syenite rich in sodalite, and having a peculiar poikilitic texture. The mode, computed from the chemical analysis and compared with the thin section, gives for two different specimens: sodalite 31 (54), nephelite 18 (5), eudialyte 3 (2), microcline 20 (6), albite 10 (—), ainigmatite —(2), aegirite 10 (12), arfvedsonite 1 (5), analcite 7 (14).

Sodalitite is almost exclusively made up of sodalite with very small amounts of aegirite, feldspar, and eudialyte.

Kakortokite is a coarse grained, trachytoid (foyaitic) nephelite-syenite. It differs from ordinary foyaite in its high percentage of dark constituents. Three varieties are described: black, white, and red. The minerals are eudialyte, alkali-feldspar, nephelite, arfvedsonite, and aegirite. Sodalite, ainigmatite, biotite, rinkite, fluorite, and epistolite, as well as zeolites, may be present. The chief minerals in the black rock are aegirite and arfvedsonite. They are present in about equal amounts and, while very abundant in other cases, make up 65 per cent of the black rock. The chief mineral of the white rock is microline-microperthite, the chief mineral of the red, eudialyte.

Agpaite is a general name given to the rocks occurring at Ilimausak, and includes the sodalite-foyaite, naujaite, lujavrite, and kakortokite.

VALETON, J. J. P. "Kristallform und Löslichkeit." *Ber. math-phys. Kl. kön. sächs. Gesell. Wiss.*, Leipzig. LXVII (1915), No. 78, pp. 59, figs. 10, pl. 1.

Determines that there is no difference in the solubility of alum in different directions. The laws of growth and solution must be explained on different grounds than solubility differences.

Van Orstrand, C. E., and Wright, Fred. E. "The Calculation and Comparison of Mineral Analyses," *Jour. Wash. Acad. Sci.*, IV (1914), 514–25.

Various methods for adjusting chemical analyses are discussed, and the conclusion is reached that the present method of direct comparison of weight percentages of chemical analyses is sufficiently accurate.

Viscont, K. *On the Fluidal Texture of Some Dike Rocks from the Neighborhood of the Granite Stock of Turgojak in the Slatoust Mining District of the Ural Mountains.* 1913. Pp. 14. (In Russian language.)

The granite intrusion of Turgojak cuts metamorphosed Paleozoic schists. Both the granite body and the country rocks are cut by two series of dikes following tectonic lines.

Wada, T., Editor. *Beiträge zur Mineralogie von Japan*, No. 5, Tokyo, 1915. Pp. 201–5, numerous figures.

Contains miscellaneous mineralogical papers by K. Jimbo, N. Fukuchi, M. Suzuki, W. Watanabe, M. Kawamura, K. Nakashima, and others.

Warren, Charles H. "The Ilmenite Rocks near St. Urbain, Quebec," *Amer. Jour. Sci.*, XXXIII (1912), 263–77, fig. 1.

The writer describes a rutile-ilmenite rock from St. Urbain, Quebec, which he proposes to call *urbainite.* Two specimens give rutile 20.4 (11.3), ilmenite-hematite 73.2 (84.5), sapphirine 3.2 (0.7), remainder 3.2 (3.2).

Warren, Charles H. "Petrology of the Alkali-Granites and Porphyries of Quincy and the Blue Hills, Mass., U.S.A.," *Proc. Amer. Acad. Arts and Sci.*, XLIX (1913), 203–330, pls. 2, sketch maps 2, chemical analyses.

The alkaline granitic magma of Quincy and the Blue Hills is believed by the author to have been intruded by stoping after Middle Cambrian but before late Carboniferous times. Having nearly reached the surface, the upper portions are rather vitreous while lower portions are more crystalline and appear as granite-porphyries. Still lower the rock is a fine-grained granite. In one portion of the field the marginal phase is

broken up and intruded by later material. Locally there is a more basic phase where the magma differentiated against the slate or even under its own cover, and the rock is rhombic porphyry. No complementary dikes occur in the region.

WARREN, CHARLES H. "A Quantitative Study of Certain Perthitic Feldspars," *Proc. Amer. Acad. Arts and Sci.*, LI (1915), 127–54, fig. 1.

Micrometric readings and calculations from analyses of eight perthites show microcline 52.3–86.2 to albite 47.7–13.8 per cent by weight. The author comes to the conclusion held by Vogt, that perthitic structure in primary potassic feldspar, where the amount of albite is less than *ca.* 28 per cent, is due to the unmixing of previously homogeneous mixed crystals.

WARREN, CHARLES H., and POWERS, SIDNEY. "Geology of the Diamond Hill–Cumberland District in Rhode Island–Massachusetts," *Bull. Geol. Soc. Amer.*, XXV (1915), 435–76, figs. 3.

Gives a geological history of the region, and describes gabbro, cumberlandite, serpentine, labradorite-porphyry, quartz-diorite, granite, riebeckite-aegirite-granite, felsite, and various porphyries.

WASHINGTON, HENRY S. "The Volcanic Cycles in Sardinia." *Cong. géol. internat.* Canada, 1913. Pp. 11.

A preliminary statement of some of the general petrological relationships of the igneous rocks of Sardinia, and the bearing of these on certain phases of magmatic differentiation.

WASHINGTON, HENRY S., and LARSEN, E. S. "Magnetite basalt from North Park, Colorado," *Jour. Wash. Acad. Sci.*, III (1913), 449–52, analysis.

A brief description of a peculiar basalt from Colorado which contains 55 per cent of iron ore. It is the only known example of extruded lava so high in iron.

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CORAL REEFS AND SUBMARINE BANKS

W. M. DAVIS
Cambridge, Massachusetts

PART III

Submarine banks in the coral seas.—Most modern writers on the coral-reef problem have followed Darwin in explaining the submarine banks of the coral seas as submerged atolls which had subsided so fast that their reefs were not built up to the sea surface; but they are regarded by Daly as representing still-standing preglacial volcanic islands, reduced first by long-continued erosion to low relief, and then by abrasion before or during the glacial period to smooth platforms, around which postglacial reefs have been less completely formed than around the corresponding platforms of ordinary atolls. Thus here again subsidence is the essential factor of the older explanation, while it is essentially excluded from the newer one. One explanation is as easily conceived as the other; the difficult matter is, as before, to find appropriate tests by which the true explanation can be determined. If the submarine banks were today all of the same depth and if they still preserved the form of very flat cones which abrasion would give them the problem might be easily solved; but their depths vary and their form is not that of flat cones but, as a rule, of shallow saucers; thus the problem

becomes complicated. The dimensions of some of the largest banks in nautical miles and fathoms are as follows:

Bank	Location	Length	Breadth	Central Depth
Macclesfield	China Sea	95	35	55–60
Tizard	" "	25	10	48
Seychelles	Indian Ocean	200	80	40
Great Chagos	" "	90	70	48
Amirante	" "	90	20	30
Namuka	Pacific Ocean	30	25	45

The Macclesfield bank, the largest of several submarine banks in the China Sea, is a good example. Interesting accounts of it have been published by the British Admiralty.[1] It possesses an incomplete rim, occupied by living corals, which rises around the margin to minimum depths of about 10 fathoms. Now if this bank has an abraded platform for a foundation, the depth of the platform should increase from the center outward and should be at least 10 or 15 fathoms more at the margin than at the center. Hence the bank margin, originally 55 or 60 fathoms and now only 10 fathoms below present sea-level, must have been built up at least 45 or 50 fathoms in postglacial time, and at half-distance from margin to center the bank must have been aggraded 15 or 20 fathoms in order to convert its initial flat cone into the present shallow saucer. But if so much change has taken place outside of the center, the center itself must have been significantly aggraded, and its actual depth is therefore not a true measure of the depth of its buried rock foundation.

The same uncertainty prevails as to the depth, not to say the very existence, of the supposed rock platforms that are assumed to serve as foundations for other submarine banks. The Great Chagos bank of the Southern Indian Ocean, taken by Darwin as the type of a drowned atoll, measures 90 by 70 miles; it has a broad, flat floor, 48 fathoms in depth near the center, and a broad rim at an average depth of 16 fathoms, from which a narrower rim rises nearer to the surface. The Amirante bank, in the same

[1] W. U. Moore and P. W. Bassett-Smith, *China Sea . . . . Tizard, and Macclesfield Banks*, Hydrog. Dept., Admiralty, London, 1889. P. W. Bassett-Smith, *Dredgings Obtained on the Macclesfield Bank, Ibid.*, 1894.

ocean, north of Madagascar, measures 90 by 20 miles, with a central depth of 30 fathoms and a rim generally under 10 or 20 fathoms of water, bearing living coral and emerging in 21 low coral islands. Even more extraordinary is the vast Seychelles bank, east of the Amirante bank, the largest example of its kind; as represented on Admiralty chart 721, it measures about 200 by 80 miles; its general depth varies from 25 to 35 fathoms, with a maximum of 40 fathoms not far from the central island, Mahé, and with a shoal margin on the northeast where several reefs and coral-sand islands reach the surface. Here, as in the Macclesfield bank, the marginal depth of an abraded platform should be significantly greater than its center, and the present central depth of the bank is no safe measure of the depth of a platform beneath it. The central island, Mahé, represented in more detail on Admiralty chart 1072, is singular in being composed of non-volcanic, granitic rocks; it measures 17 by 4 miles, and its highest summit rises 2,993 feet above sea-level; its shore line is not clift, but beautifully embayed, with the bayheads occupied by delta plains and the dividing spurs trailing away in declining points with no cliffs at their ends.[1] Discontinuous fringing reefs border the points. Several other smaller granitic islands rise not far away.

Mahé has, moreover, not only a narrow fringing reef at present sea-level, but also at a height of 80 feet patches of an elevated fringing reef,[2] which must, like the sea-level fringe, lie unconformably on the granitic slopes of the island; the date of the elevated reef with respect to the date of origin of the great submarine bank has not been studied by any of the visitors to the island—Pelly, Wright, Coppinger, Keller, Chun, Gardiner—whose accounts I have read; but if the elevated reef be the older of the two, it ought to have been completely worn away while the great bank, whatever its origin, was forming; and if the reef be the younger of the two, then while it was forming the great bank must have had a maximum

[1] Good views of the Mahé shoreline are given by C. Keller, *Die ostafrikanischen Inseln* (Berlin, 1898), p. 160; C. Chun, *Aus den Tiefen des Weltmeeres* (Jena, 1900), p. 432; and J. S. Gardiner, "The Indian Ocean," *Geogr. Jour.*, XXVIII (1906), 313–32, 454–65; see p. 457.

[2] C. Keller, *op. cit.*, p. 158; C. Chun, *op. cit.*, p. 426.

depth of over 50 fathoms, and the bank would then be even more difficult of explanation by the glacial-control theory than it is when considered without regard to the elevated reef. However, perhaps the elevated reef, if it really occurs, is only a remnant of a much larger ancient reef which was, after elevation, eroded to its present moderate dimensions while the great bank was forming; in this case it would cause no embarrassment, provided the formation of the bank would not require so long a time as to involve the complete removal of any pre-existent reef and the partial erosion of the granitic foundation as well. The study of Mahé by the zoölogists and oceanographers who have visited it has not included an attack on this problem.

The absence of spur-end cliffs on this granitic island discountenances the idea that it rises from an abraded platform; and to this it may be added that, not only the breadth of its bays, but also the strong unconformity between the sea-level fringing reefs and the granitic points which they adjoin, indicates a greater measure of erosion beneath present sea-level than could have been accomplished while the ocean was lowered during the glacial period; and this calls for subsidence from a former higher stand.

Namuka bank, the largest of several banks in the Tonga or Friendly islands of the South Pacific, is peculiar in having a slanting surface; it is 30 fathoms deep on the eastern side, where it is rimmed by a reef that rises toward or to the surface; it inclines gradually to the western, reefless margin, where its depth varies from 50 to 70 fathoms. Hence this bank has probably been tilted since it was formed. Other banks in the Tonga group also suggest recent deformation; none of them confirm the assumption that their foundations have enjoyed a long-enduring stability.

As compared with the profound basins of the ocean, submarine banks may be all described together as having small and similar depths; but when separately examined their individual depths vary by large fractions of their mean depth. If large and small banks are compared their depths are in a general way found to decrease with their diameters, but there are many departures from this rough rule. The vast Seychelles bank (40 fathoms) is not so deep as the Great Chagos (48 fathoms) and the Macclesfield (55–60

fathoms) banks; the smaller banks are usually 25 fathoms deep, but the smallest are about as deep as the middle-sized banks: thus Turpie bank, 23 miles long, is 27 fathoms deep; for Alexa bank the figures are 18 and 24; Waterwitch, 10½ and 25; Penguin, 9 and 25; Hazel Holme, 5 and 25. The Saya de Malha bank in the Southern Indian Ocean southeast of the Seychelles bank is most exceptional in this respect; although only about 20 miles in diameter it has a central depth of 64 fathoms, with a rim of 20 fathoms or less around the northeastern margin. I have not been able to conceive of any way to account for this bank under the postulates of the glacial-control theory.

As to banks of moderate size and of 20 or 25 fathoms depth, any platform that lies beneath them should be as deep as, indeed somewhat deeper than, the platforms of the great banks; hence the thickness of the deposits by which the smaller banks are aggraded must measure at least 20 or 30 fathoms; but as this measure is obtained only by assuming that the platform exists at a proper depth, it has no particular value.

It is interesting to note in passing that the central areas of the smaller reef-rimmed banks have extraordinarily smooth floors, presumably the work of the heavy swell that must sweep across their submerged rims and distribute very evenly all available sediments. It was, indeed, the smooth floors of these banks that led Wharton to abandon Darwin's theory of subsidence, which he conceived as requiring a "deeply concave surface" in the floors of atolls, whether their rims be at sea-level or below; he suggested instead that the flat floors of atoll lagoons and of submarine banks represented former volcanic islands, smoothly truncated by the waves of the ocean at its present level,[1] and he tacitly postulated that reef-building corals were not present until the work of abrasion was completed. Daly gives a more reasonable statement of the conditions under which abrasion could act, but in saying, "Wharton's choice of the agency which produced the flatness of lagoon floors and of banks seems irresistible," he does not make sufficient distinction between the evenly aggraded, reef-rimmed floors of the smaller submarine banks at such depths as 20 and 25 fathoms, and

[1] W. T. L. Wharton [Address], *Rep. Brit. Assoc. Adv. Sci.* (1894), pp. 699–710.

their supposed abraded platforms, which according to the glacial-control theory should be some 20 fathoms deeper; and in adding that Wharton "rightly regarded this flatness as fatal to the Darwin-Dana theory" (196), he disregards the capacity of lagoon waves in true atolls and of the ocean swell over submerged atolls or banks to produce smooth lagoon floors, whatever the form of the buried foundation. This capacity seems to me well proved. Hence, as far as the features of atolls and submarine banks are concerned, the necessity of accepting the glacial-control theory is not constraining; the possibility of accounting for the form and the depths of atoll-lagoon floors and of submarine banks as a result of their slow, variable, intermittent subsidence is still open.

Supposed abraded platforms beneath submarine banks.—The variations in the depths of atoll-lagoon floors and of submarine banks, although of considerable measure, are, with the exception of the Saya de Malha bank, by no means so great as to be altogether incompatible with the existence of abraded platforms at uniform depths beneath them, as required by the glacial-control theory; but they seem to me too great to demonstrate the correctness of that theory to the exclusion of all others. On the contrary, they throw a certain amount of doubt upon the theory by the necessity that they impose of making a number of unproved, perhaps unprovable, assumptions in order to bring about a sufficient agreement among various unlike quantities. This doubt may be solved arithmetically by saying: "Since probably not more than 5 to 25 m. can be allowed for the thickness of the post-glacial calcareous veneer in the wider lagoons, the accordance of platform depths for the wider lagoons and reefless banks seems clear. . . . . The agreement is visible in spite of possible, though necessarily slight, uplift or subsidence" (Daly, 193, 194); but such a solution is not convincing. It involves the venturesome postulate of a long-enduring still-stand of the islands concerned, the very questionable process of abrasion while the reefs were supposedly dead, and the entirely unknown total thickness of calcareous deposits in lagoons and on banks. A solution containing so many undetermined quantities must remain very uncertain. The uncertainty will be more apparent if we return to the case of the

Macclesfield bank, which is instanced as typical of its class, and inquire particularly as to the validity of the assumptions that are necessary in order to explain it by the glacial-control processes. The assumptions appear to be about as follows:

If a volcanic island about the size of Hawaii stood still long enough in preglacial time, it would be reduced to low relief and would be surrounded by shoals of its own detritus mingled with reef deposits. If any defending reefs were killed by the chilled and lowered glacial ocean, the low island would be attacked by the waves; and, if the attack endured long enough, the island, still stationary, would be reduced to a smooth platform having the form of a very flat cone. Such a platform would have about the area of the Macclesfield bank. Then as the sea finally warmed and rose again the bank would be more or less rimmed with a reef and aggraded with wave-swept sediments. This succession of suppositions is, like many another, easily conceivable; but it is so full of improbabilities that it cannot command acceptance, as the following considerations will show.

The instability of the Australasian Archipelago.—The improbability that wave attack was effective in truncating preglacial islands has already been sufficiently set forth; some uncertainty as to the lowering of the glacial ocean by so much as 35 or 40 fathoms will be pointed out below in the section on extra-tropical submarine banks; we may here inquire whether the region of the Macclesfield bank can be fairly regarded as one of long-enduring stability. No inquiry based on geological evidence regarding the region concerned appears to have been made on this point. Stability seems to have been assumed in order that an even platform might be abraded and a smooth bank formed by subsequent aggradation. If this assumption be temporarily set aside, the geological relations of the bank may be inquired into impartially. The general situation of the bank in a deep sea on the border of a large continent is not one that would be chosen, on general principles, as presumably stable. The prevailing opinion as to the instability of continental borders is summarized by Chamberlin and Salisbury, who suggest that mutual crowding and crumpling may take place, accompanied by fracture and slipping, where the edges of elevated continental

segments and of depressed oceanic segments of earth's crust adjoin; and that tracts of low resistance to deformation may be expected at or near the border of continents, "where the crust is already flexed in its descent from the continental platforms to the ocean bottoms."[1]

Furthermore the China Sea, from the depths of which the Macclesfield bank rises, is bordered by embayed coasts on nearly all sides. The embayments of the coast of China in the Hong Kong district are manifestly due to the submergence of a maturely eroded mountainous area; the reef-free headland points are little clift, and the breadth as well as the probable rock-bottom depth of the bays appears to be greater than could have been produced by subaërial erosion during the glacial epochs of the glacial period; thus recent subsidence is indicated on that side of the China Sea. On the east the sea is inclosed by the Philippine Islands, where diverse earth movements of modern geological dates are abundantly proved. The southern part of the sea, where Tizard and other submarine banks rise, is inclosed on the east by the long island of Palawan, the southernmost member of the Philippine group, with a wonderfully embayed coast, as shown on Admiralty chart 967, or better on United States Coast Survey chart 4316; its headlands are not clift and are almost free from fringing reefs; they have a rapid descent to depths of from 15 to 25 fathoms close to the shore line. The chart has every appearance of accuracy; hence the absence of cliffs on the delicate spur-end points between the intricate embayments is significant. A submarine bank stretches westward from the embayed shore line; it is from 15 to 30 miles wide and from 40 to 60 fathoms deep near its outer margin, where it is rimmed by an imperfect barrier reef that rises discontinuously toward the sea surface. It seems impossible to regard this broad bank as the work of abrasion, because the headlands of the coast behind it are not clift; it seems equally impossible to regard the broad embayments of the coast as the product of subaërial erosion during the epochs of lowered sea-level in the glacial period, because of their great width; recent and rapid subsidence of a reef-fronted coast is thus strongly indicated. Farther north the west coast of Luzon is much less embayed than Palawan and is without a broad off-shore bank;

[1] *Geology*, I (1904), 522; II (1904), 127.

here, according to Becker, elevation has predominated in late Tertiary and post-Tertiary time; thus differential movements of Palawan and Luzon are suggested. Other differential movements of late date within the Philippines are abundantly proved by various records, such, for example, as the elevated reef terraces briefly described by Becker as occurring on the islands of Cebú and Negros (see below) but absent on neighboring islands. Evidence of recent and rapid subsidence in some of the Philippine Islands, as shown by their narrow, unconformable fringing reefs, will be presented in a forthcoming article in the *Bulletin of the Geological Society of America*.

But besides all this it must be remembered that the China Sea is, unlike the shallow Yellow Sea on the north and the shallow Java Sea on the south, one of those deep mediterraneans that are inclosed along the eastern border of Asia by festoons of islands in which, geologically, modern movements are the rule. Darwin wrote of this region, "Between the Indian and Pacific oceans . . . . north of Australia, lies the most broken land on the globe, and there the rising parts are surrounded and penetrated by areas of subsidence" (143). He had little evidence on which to base his statement, but he was right. Molengraaff much later characterized the same region as follows:

> In the eastern part of the archipelago (between Borneo and Australia) where a complicated topography of the land and the sea bottom prevails, deep-sea basins have been formed by subsidence [in the "latest geological periods"], and, during the same time, ranges of islands have been raised above the sea, caused by antagonistic movements which are probably still in progress.[1]

The same writer cites from the report of the Dutch "Siboga" expedition a remarkable dredging record made on September 1, 1900, for the middle of the Ceram Sea, between Celebes and New Guinea:

> From a depth ranging from 1,633 to 1,304 m. over a distance of no less than three nautical miles, large quantities of recent, reef-building coral were there dredged, which . . . . by a thick cover of manganese revealed their long stay in the sea-water. . . . . The nearest point in these regions where living reef-building corals occur near the surface lies at 42 kilometers from the point where the dredging took place. . . . . In order to explain the result of this dredging

[1] G. A. F. Molengraaff, "On Recent Crustal Movements in the Island of Timor," *Proc. k. Akad. Wet. Amsterdam*, XV (1913), 224–35.

I should rather suppose that on that spot in the Ceram Sea . . . . a drowned coral island rises to about 1,300 m. below sea-level. Such a supposition seems justified if it is borne in mind that the Ceram Sea is one of the most remarkable trough-shaped deep basins in the eastern part of the Indian archipelago, the origin of which is probably connected with crust movements in Pleistocene and post-Pleistocene times. They were formed by downward movements, simultaneous with, and more or less compensated by, elevations of about equal amount of other parts.[1]

The crustal instability inferred for the Ceram Sea is not exceptional. Recent studies in other parts of the great archipelago attest a wide extension of diverse movements in late geological times. Thus the Sarasin brothers infer various movements of Celebes in modern geological periods,[2] and more detailed studies of the same island by Ahlburg and Abendanon reach similar conclusions. The first of these two investigators has published a monograph in which various changes of island level are described.[3] The second has given an abstract of his report on a geological and geographical traverse of middle Celebes in the *Journal of the Dutch Geographical Society;* it is there stated that a region of crystalline rocks which was reduced to a peneplain in Oligocene time has suffered great displacements in later periods, including plio-Pleistocene upheavals of 1,000 meters, and subsidences of similar measure; the deepening of the adjoining seas is explicitly stated to have accompanied the elevation of land areas, thus indicating strong differential movements.[4] Many other articles might be cited to the same conclusion. Thus Becker[5] and Smith[6] both testify to diverse movements in the

[1] G. A. F. Molengraaff, "The Coral-Reef Problem and Isostasy," *Proc. k. Akad. Wet. Amsterdam,* XIX (1916), 610–27; see p. 624. Fine charts of the Australasian mediterraneans are given by G. F. Tyddeman, *Hydrographic Results of the Siboga Expedition,* Leiden, 1903.

[2] P. and F. Sarasin, *Ueber die geologische Geschischte . . . . der Insel Celebes,* Wiesbaden, 1901.

[3] J. Ahlburg, "Versuch einer geol. Darstellung der Insel Celebes," *Geol. and Pal. Abh.,* XII (1913), heft 1.

[4] E. C. Abendanon, "Historische Geologie van Midden-Celebes," *Tydschr. k. ned. Aardr. Gen.,* XXIV (1917), ?–456, 548–64.

[5] G. F. Becker, "Report on the Geology of the Philippine Islands," *U.S. Geol. Surv., 21st Ann. Rept.,* 1901, Part III, pp. 1–139; see pp. 19, 69.

[6] W. D. Smith, "Contributions to the Physiography of the Philippine Islands. I, Cebú Island," *Phil. Jour. Sci.,* I (1906), 1043–57.

Philippines: Becker states that there is a great unconformity on Cebú and Negros between the Miocene lignitic series and the coral-limestone mantle, which in Cebú extends to an altitude of 2,362 feet; Smith gives an account of the island of Cebú, the strata of which have suffered profound folding and much erosion followed by submergence, reef formation, and emergence.

Instability of this region is also to be inferred from the mention of disturbed Tertiary deposits in Kotô's account of the Malayan Archipelago,[1] and in Richthofen's essay on "Formosa and the Riukiu Islands."[2]

In view of the accordant testimony of all these observers it would seem that the deep mediterraneans on the eastern border of Asia have presumably suffered deformation in modern geological time, and that long-enduring instability is by no means a probable characteristic of the Macclesfield bank. Indeed, as Suess[3] and others have suggested, the deepest seas are, like the highest mountains, very likely due to modern deformation. If one were asked to select a deep-sea area where rapid subsidence might be expected and where drowned atolls might therefore occur, and where long-continued stability appears improbable, the China Sea would seem to be about as good an example as any other. The Central Pacific has probably suffered much less deformation of recent date than the China Sea and its neighbors; and yet there are signs of subsidence even in the Central Pacific, as was pointed out in the accounts of Hawaii and Tahiti, previously given.

Subsidence or stability in the Indian Ocean.—As to the great submarine banks of the Indian Ocean, they are so remote from continents and large islands of decipherable history that speculation regarding their origin is not narrowly limited. Little help toward reaching a sound conclusion concerning them is found in the published opinions about the small islands of the Indian Ocean. For example, C. W. Andrews (not to be confounded with E. C. Andrews,

[1] B. Kotô, "On the Geologic Structure of the Malayan Archipelago," *Jour. Coll. Sci. Tokyo*, XI (1899), 83–119.

[2] F. V. Richthofen, "Geomorph. Studien aus Ostasien: III, Die morphol. Stellung von Formosa und den Riukiu Inseln," *Sitzungsber. Akad. Wiss. Berlin*, 1902.

[3] E. Suess, *Das Antlitz der Erde*, III (1909), 336.

of Sydney, New South Wales), who was sent from England to study Christmas Island, an elevated atoll nearly 1,200 feet high in the eastern part of the Indian Ocean, seems to have followed the belief announced by Suess regarding the elevated Loyalty atolls of the Western Pacific; for, although he recognized that the basal limestones of shallow-water deposition must have been depressed in order to be covered by hundreds of feet of later limestones, he afterward suggested that the altitude of Christmas Island might not be due so much to a local uplift of 1,200 feet from an ocean of stationary level as to a subsidence of the ocean by 1,200 feet while the island stood still;[1] he thus, perhaps unintentionally, implied that all the ocean bottom elsewhere recently subsided 1,200 feet, and that all the islands and all the continents which did not emerge at the same time by the same amount also subsided with the ocean; or else that a smaller part of the ocean bottom subsided by a proportionately greater amount. If we could follow this author's lead we should not hesitate to explain the submarine banks of the Indian Ocean by subsidence, for a hypothesis which accounts for the local emergence of a small island by a great and widespread sinking of the ocean bottom elsewhere need not shrink from explaining submarine banks by a subsidence of 40 to 50 fathoms. But for my own part I can find little support for the subsidence theory of coral reefs in a hypothesis so reckless as that which accounts for the emergence of Christmas Island by a sinking of most of the rest of the world; hence we must look elsewhere for evidence as to the behavior of the Indian Ocean bottom.

We thus come to Gardiner's study of the Maldive atolls which led him to reject recent subsidence; for, although he accepts the depression of a large land area between India and Madagascar in Tertiary time, he asserts that "this depression is not the same as the slow and long-continued subsidence postulated by the upholders of Darwin's theory," and then, "seeing the absolute impossibility of subsidence affording any explanation" for the Maldives, he concludes that "an almost flat plateau at a depth of 140 to 170 fathoms was at one time formed by the erosion and denudation of

[1] C. W. Andrews, *A Monograph of Christmas Island* (*Indian Ocean*) (London, 1900), p. 298.

an original [still-standing] land mass, or more probably series of masses," and that the present shoals and reefs were afterward built up from the plateau to the sea surface.[1] He thus assumes, as Wharton did in his abrasion theory of atolls, that destructive processes first wore down a non-subsiding land mass or series of masses to a certain depth—in the case of the Maldives to the considerable depth of 150 fathoms—and that organic agencies, which must have been in abeyance while the down-wearing was in progress, then proceeded to overcome the destructive processes and to build up the present shoals and reefs. A hypothesis which accounts for the Maldives by upgrowth on a series of worn down, still-standing land masses might also explain a number of large submarine banks, imperfectly reef-rimmed, as still-standing masses that have been similarly worn down and are not yet completely built up again; but neither the postulates nor the processes of this hypothesis commend it.

Between the two extremes thus instanced Darwin's theory of reef upgrowth during intermittent subsidence seems to me a happy mean. Darwin applied his theory to the Maldives in a manner that is still consistent with the best interpretations of oceanographic problems; he regarded those numerous atolls in linear arrangement as resulting from the disseverment of a great barrier reef upgrowing from a slowly subsiding foundation

> of nearly the same dimensions with that of New Caledonia . . . . for if, in imagination, we complete the subsidence of that great island, we might anticipate from the present broken condition of the northern portion of the reef . . . . that the barrier reef, after repeated subsidences, would become during its upward growth separated into distinct portions; and these portions would tend to assume an atoll-like structure, from the coral growing with vigour round their entire circumferences, when freely exposed to an open sea [110].

Similarly Darwin's explanation of submarine banks by subsidence is more in accordance with all pertinent facts than is any explanation which involves their long-enduring stability. Whether the failure of reefs to grow up from such banks to the surface again is due to rapid subsidence, as Darwin thought, or to the injurious

[1] J. S. Gardiner, "The Origin of Coral Reefs," *Amer. Jour. Sci.*, XVI (1903), 203–13; see pp. 205, 206.

effects of "clouds of sediments" (211), as Daly suggests, this cause of failure being evidently as applicable to a drowned atoll as to an abraded platform, is a good subject for future investigation.

It is not only in general, but also in certain details that the theory of subsidence applies to the reefs of the Indian Ocean. Gardiner notes that "a most important point of difference in the Maldives from north to south lies in the gradual increase of the banks [lagoon floors] in depth," but as recent subsidence is to him an "absolute impossibility" he finds no satisfactory explanation for the increase. The large-scale Admiralty charts of the Maldives show the northern lagoons to be from 20 to 25 fathoms deep, and the southern ones from 40 to 45 fathoms, the change being accomplished in about 400 nautical miles. Darwin knew these facts and said in the first edition of his book, "I can assign no adequate cause for this difference in depth" ('42, 34), but he added in the second edition, "excepting that the southern part of the Archipelago has subsided to a greater degree or at a quicker rate than the northern part" ('74, 47). No one has since then offered any better explanation. It may be added that the Great Chagos bank lies about 300 miles south of the Maldives, and therefore Darwin's interpretation of it as a drowned atoll falls in very well with his explanation of the southward deepening of the Maldive lagoons. When one recalls the various lines of geological evidence that point to the change of a large land area to a deep-sea bottom in the western part of the Indian Ocean, it seems as unreasonable to exclude recent subsidence from this region as to exclude it from the center of the China Sea.

Control of depth of submarine banks.—It is not only the flatness of submarine banks that has been regarded as beyond explanation by the subsidence theory; the accordance of their depths with respect to present sea-level has also been instanced as impossible of explanation by any other cause than prolonged abrasion of still-standing islands by the lowered glacial ocean. As to their origin by abrasion, suffice it to repeat the argument already stated, namely, if preglacial islands of almost any composition as broad as the larger submarine banks were completely truncated by the waves of the lowered glacial ocean, then the spur ends of maturely

dissected volcanic islands encircled by close-set barrier reefs ought today to be cut off in cliffs, the face of which, where not obscured by apposed deposits, should descend some tens of fathoms below present sea-level. This argument applies with special force if the great Seychelles bank be considered; for there the several granitic islands that are still visible strongly suggest that any large preglacial island occupying much of the area of the bank would have included a good proportion of resistant rocks in its constitution, and such an island could have been reduced to a platform of abrasion only by strong wave work continued long enough to cut spur-end cliffs on smaller volcanic islands elsewhere, around which narrow preglacial reefs were the only defense.

The inconsistency of the glacial-control theory in demanding broad abrasion for large atolls and submarine banks and in allowing only narrow abrasion around high volcanic islands within fringing or close-set barrier reefs is not, to my mind, satisfactorily explained by assuming that the atolls and banks were all represented in preglacial time by the deeply weathered, weak rocks of old, worn-down, still-standing islands, while the high islands were composed of resistant rocks of younger islands; for there is nothing to support such an assumption as to the preglacial representatives of atolls and banks except the consequence that is desired to follow from it; indeed the granitic islands of the Seychelles group contradict the assumption. Still less has a satisfactory explanation been offered for the other inconsistency—pointed out on page 294 in the account of Murea—of demanding that comparatively broad valleys must be eroded with respect to the lowered sea-level of the glacial period by the action of slow-working subaërial processes on the resistant rocks of high volcanic islands in the mid-Pacific area of assumed stability, and of denying that rock platforms and spur-end cliffs of significant dimensions can have been abraded in the same rocks while they were undefended by living reefs and attacked by the vigorous waves of the trade-wind seas during the same period of time as that in which the broad valleys were eroded. Nor can a satisfactory explanation of this inconsistency be found without concluding that the non-clift islands were protected all through the glacial period by living reefs. The upshot of this is that submarine

banks should not be regarded as the product of abrasion acting on still-standing reef-encircled preglacial islands while the ocean was lowered in the glacial period.

As to the depths of submarine banks being so accordant as to be beyond explanation, except as a consequence of abrasion at some such depth as 35 or 40 fathoms: It has already been pointed out that the actual depths are discordant, for they vary from 20 or 25 fathoms in the smaller banks north of Fiji to 40, 50, or 60 fathoms in the large banks of the China Sea and Indian Ocean, and to 64 fathoms in the exceptional Saya de Malha bank. Accordance is found only by subtracting larger measures of postglacial aggradation from the depth of the shallower banks and smaller measures from the depth of the larger banks; and even then the depth of the Saya de Malha bank is not brought into accord with that of its fellows. Daly has pointed out, as has been previously noted, that small banks are, on the average, shallower than large ones, and has explained this relation by showing that small banks should be more rapidly aggraded than large ones, in so far as the detritus is supplied from their rim; but according to this principle small atolls drowned by subsidence should also be more rapidly aggraded and therefore shallower than large ones: hence these variations of depth cannot serve as ground for valid choice between the two theories. As the depth of actual aggradation of submarine banks is absolutely unknown, measures of aggradation satisfactory to either theory may be freely assumed, but neither theory is thereby strengthened. Choice between them must be made on other grounds.

Possible balance of processes acting on submarine banks.— It is evidently conceivable that all the banks mentioned above may be neither drowned atolls built on subsiding foundations, nor ancient still-standing islands reduced to abraded platforms now more or less aggraded, but still-standing submarine masses of any origin now for the first time in process of building up toward sea-level, as postulated in the Rein-Murray theory of atolls. This conception cannot be proved or disproved by soundings; it can be tested only by indirect evidence, such as is afforded by the history of adjacent islands or continents and by the general action of organic

processes and of waves and currents. The history of adjacent islands indicates, as has already been shown, that long-enduring stability is not a necessary condition of the ocean floor in general, and that it is by no means a probable condition of the parts of the ocean floor where certain submarine banks occur. As to the accumulation of organic deposits on submarine banks, that is manifest enough; but the mere occurrence of such deposits does not prove that the banks are standing still instead of rising or sinking, or that loose deposits can aggrade a bank to small depths in the open ocean where heavy swell frequently sweeps over it. The submarine banks described by Buchanan[1] and Murray[2] may or may not exemplify the Rein-Murray theory of atolls; they certainly do not demonstrate its correctness.

In view of the slow accumulation and continual disintegration of organic sediments and of the increasing action of waves and currents upon them as their depth decreases, it is possible that the depth of submarine banks may be in some instances controlled through a rough balance between degradation by waves and currents as well as deepening by slow subsidence and aggradation by accumulating sediment. Whatever their origin, the accumulation of organic detritus will tend to build up the surface; and here be it noted that although aggradation by inwash of detritus from a drowned reef rim is less effective in large banks than in small ones, aggradation by precipitation of floating organisms and by accumulation of bottom organisms is not affected by area; for the larger the area the more numerous the organisms; a very large bank may therefore be built up about as fast as one of medium size. On coral reefs there are numerous agencies, from gnawing fish and grinding sea slugs to boring worms and adhering algae, which reduce coral rock to sand and silt of such fineness that it can be easily shifted by the waves and currents of the lagoons. If similar disintegrating

[1] T. Y. Buchanan, "On Oceanic Shoals Discovered by the SS. 'Dacia' . . . . ," *Proc. Roy. Soc. Edinb.*, XIII (1886), 428–43. These banks and several others off the coast of Africa between the Canary Islands and Spain are shown on Hydrogr. Office chart 1743; they are all less than 10 miles in diameter; their depths vary from 23 to 96 fathoms.

[2] J. Murray, "Balfour Shoal, a Submarine Elevation in the Coral Sea," *Scot. Geogr. Mag.*, XIII (1897), 120–34.

agencies are at work on submarine banks, the fine detritus that they produce would be lifted from the shoal surface by the waves and currents and deposited on the steep exterior pitch; and the nearer the surface of the bank stood to the surface of the sea the more active would this process be.

Evidently, then, if a former atoll were transformed into a submarine bank with a depth of 60 or 70 fathoms at a time of active subsidence, it might be aggraded to a depth of 50 or 40 fathoms during a following time of still-stand; but further reduction of depth might be long prevented by wave work if no coral rim were built up around the margin of the bank. Hence, if still-stand periods are commonly of long duration and times of active subsidence are short-lived, a rough approach to similarity in the depth of banks would ordinarily prevail; banks of unusually great depth would occur only here and there for a relatively short period after active subsidence and would therefore be exceptional. In the case of submarine banks that have not subsided from a former existence as islands, but that have been built up by volcanic eruptions to such depths as 200 or 100 fathoms and have then stood still, a similar balance might be reached when their depth was reduced by organic aggradation to the critical level. As was previously noted, whatever truth there is in this supposition will militate against the acceptance of the Rein-Murray theory, which accounts for atolls by the progressive aggradation of still standing banks until they are brought to so small a depth that reef-building corals can be established upon them.

Need of oceanic exploration.—It seems improbable, however, that subsidence, if it be really so dominant an oceanic process as Darwin's theory implies, should not in some cases overcome aggradation and carry some banks down to such depths as 100 or 200 fathoms. The scarcity of large flat banks at such depths is manifestly a difficulty that the theory of reef upgrowth does not fully overcome. It is of course possible that further exploration of the ocean depths will discover additional examples and show that they are not so rare as they now seem to be; and inasmuch as there are unsounded areas in the Pacific as large as Australia, this possibility may be almost a probability; nevertheless, as long as

the facts are not more fully ascertained, the rarity of deep banks is, in my view, more unfavorable to Darwin's theory than any other objection that has been urged against it.

It may be noted that certain small sea-level reefs in Fiji appear to have been recently submerged by subsidence to a depth of 100 fathoms or more, after a previous appearance at sea-level and before their present emergence by elevation; they stand near the lofty atoll of Vatu Vará, which is now 1,030 feet above sea-level; at an earlier time, when the presumable foundation of Vatu Vará may have stood about as high as now so that a reef could begin to grow upon it, the small reefs also may have had their heads at sea-level; between then and now, when the reef of Vatu Vará was completing its upward growth upon its supposedly subsiding foundation, the small reefs must have been deeply submerged, because their small size prevented their continued upgrowth; I have suggested that they might then be called "extinguished," and that now, since they have been brought to the surface again by uplift, they might be called "resurgent."[1] It may be further noted that several lines of evidence, of which the latest one to be announced is found in an article by Foye,[2] indicate a recent eastward tilting in the eastern part of Fiji, and that some small submerged banks lie beyond the easternmost islands, as if the tilting in their district were too great to be overcome by upgrowth. Close-spaced soundings in that region would be of special interest. A tilting is also indicated to the northwest of Viti Levu, the largest Fiji island, as has been noted; there also additional soundings are desirable.

Extra-tropical submarine banks.—If prolonged crustal stability characterizes the intertropical oceanic areas in which volcanic foundations are crowned with atolls, it should also characterize extra-tropical oceanic areas where volcanic foundations are not reef crowned. Preglacial volcanic islands in these areas as well as atolls on the border of the coral zone, where the reefs must surely have been killed, should therefore be more or less completely reduced to submarine platforms of the same depth as the platforms that are supposed to underlie the submarine banks of the coral seas.

[1] "Extinguished and Resurgent Reefs," *Proc. Nat. Acad. Sci.*, II (1916), 466–71.

[2] "The Geology of the Lau Islands [Fiji]," *Amer. Jour. Sci.*, XLIII (1917), 343–50.

Large-scale ocean charts show that shallow platforms or banks do surround a number of extra-tropical volcanic islands, but the recorded depths do not correspond to the depths that abraded platforms must have, if they exist, beneath the great submarine banks of the coral seas. Just as the central depths of coral-crowned banks are the most significant measures there offered, so the central depths of extra-tropical banks—or the depths close around their residual, cliff-rimmed islands—are also the most significant, because in both cases these central depths give the nearest indication of the attitude of sea-level when abrasion was taking place. It is true that the central surface of abrasion may have been worn somewhat below sea-level and that it may have been since then somewhat aggraded; but as both these variations may have similar values in all cases, it remains true that the central depths are the most significant for our purposes. The following examples may be cited.

Two small volcanic islands, Bird and Necker, in the northwestern extension of the Hawaiian group, have been described by Elschner[1] as rising with strongly clift borders of resistant lavas from extensive banks, one or two score miles across. Bird Island, latitude 23° N., is 900 feet high; its bank has depths of from 12 to 20 fathoms near the island; Necker Island, latitude $23\frac{1}{2}$° N., has a height of 300 feet; its bank has depths of less than 10 fathoms for a quarter-mile from its cliffs. Both banks deepen to 40 or 50 fathoms at their borders. It is noteworthy that coral reefs occur not far away, and it is therefore eminently possible that reefs may have been formed on these island banks also, either in preglacial time or in an interglacial epoch, the latest of which was, according to glacialists, longer and warmer than the present postglacial epoch. But if this be the case, the presence of strong cliffs on the residual volcanic islands here makes the absence of spur-end cliffs on the reef-encircled islands of the torrid seas all the more significant.

In the South Pacific, Norfolk Island, a volcanic mass in latitude 29° S., between New Zealand and Australia, is strongly clift,

[1] C. Elschner, "The Leeward Islands of the Hawaiian Group." Reprinted from the *Sunday Advertiser*, Honolulu, 1915.

according to Carne[1] and Laing.[2] Its cliffs rise 250 feet above sea-level and form a wall-like coast with few indentations; it surmounts a vast bank which is represented on British Admiralty charts 215 and 1110 as measuring 60 miles north and south by 20 miles in breadth, with depths of 20 fathoms near the island and of 40 or 50 fathoms near the margin. Similarly, Lord Howe Island, east of Australia, in latitude 32° S. (not to be confounded with a great atoll sometimes given the same name, but better known as "Ongtong Java," north of the Solomon group), presents, as described by Etheridge,[3] a ragged and clift margin on its convex northeastern side, and a coral reef inclosing a narrow lagoon on its concave south-western side; it is shown on Admiralty chart 2014 to rise from a bank from 8 to 12 miles in diameter, submerged to depths of from 20 fathoms near the island to 40 fathoms near the bank margin. Not far away the gigantic volcanic stack, known as Balls Pyramid, with a height of 1,816 feet that exceeds its shorter diameter at sea-level, rises from a 3×7-mile bank, with cliff-base depths of 15 or 20 fathoms, and marginal depths of 40 or 50 fathoms. As in the case of Bird and Necker islands, these two southern examples may have been reef-encircled in preglacial or interglacial time, and may have suffered abrasion after the reefs were dead; but if so the reefs around the islands of the torrid sea cannot have been killed, for those islands are as a rule not clift.

Mention may be made in this connection of certain exceptional intertropical islands that, like Tahiti and part of Hawaii, do possess clift spur ends. Tutuila, the easternmost of the three larger Samoan Islands, is ancient enough to be more or less dissected, and yet modern enough to be still mountainous; it is well embayed, and some of the bays at least seem to be drowned erosional valleys and not merely unfilled spaces between adjacent volcanic masses; but on this significant though elementary point no sufficient evidence is available. According to Hydrographic chart 90, the salient

[1] J. E. Carne [Notes on Norfolk Island], *App. H., Ann. Rep. Dept. Mines N. S. W., for 1885* (Sydney, 1886), pp. 145–47.

[2] R. M. Laing, "Notes on the Chief Physiographic Features of Norfolk Island," *Trans. N. Z. Inst.*, XLV (1913), 323–26.

[3] R. Etheridge, "The Physical and Geological Structure of Lord Howe Island," *Mem. Austral. Museum, No. 2.*

points of the island are rather strongly clift, and depths of 15 or 20 fathoms are shown close to the cliff base. Mayer has recently announced the occurrence of cliff-base benches 8 feet above present sea-level, and of a fringing reef that surmounts a submerged platform about 20 fathoms in depth; but he does not explicitly correlate the origin of the valleys, now drowned in embayments, and the headland cliffs, some of which are 500 feet high.[1] The Marquesas Islands, farther east in the Pacific and much nearer the equator than the many atolls in the neighboring Paumotu group, have no reefs, though fragments of coral are found in the bay-head beaches; their headlands are strongly clift, and the depths of from 12 to 20 fathoms are found a short distance offshore. Both of these examples strongly suggest that unprotected modern volcanic islands may have their spur ends clift by the ocean while valleys are eroded on their slopes; both suggest also that, as Dana suggested for the Marquesas and as Darwin pointed out in more general form, rapid subsidence may have drowned former reefs; if so, the subsidence must have been of so recent a date that no new reefs have yet been built up. These two island groups deserve abundant soundings on their banks and critical physiographic study of their shore lines.

If we assume for the moment that none of the islands here mentioned have subsided, several inferences may be drawn from the foregoing facts. The first is that the central depths of the extra-tropical banks, generally 20 fathoms or less, are decidedly smaller than the central depths of the large intertropical banks, which usually measure 40 fathoms or more; in both cases the banks may now be more or less aggraded, but no changes of depth thus brought about permit us to regard the present dissimilar depths as accordant and hence as confirmatory of abrasion at the same level by the lowered glacial ocean. Another inference is that of the two groups of banks it may well be the extra-tropical that are best ascribed to abrasion by the lowered ocean, because a lowering of sea-level by 20 or 25 fathoms, which would suffice to cut these banks, is in the opinion of some glacialists a more probable measure of the glacial lowering of the ocean than 40 or more fathoms, which is demanded for the cutting of the intertropical banks.

[1] A. G. Mayer, "Coral Reefs of Tutuila . . . . ," *Proc. Nat. Acad. Sci.*, III (1917), 522–26.

A third inference is that, as the extra-tropical clift islands present no signs of a bench abraded in preglacial times at present sea-level, such a bench, if it ever existed, must have been completely destroyed by the undercutting of the present bench; to be sure, no bench would have been cut if the islands had been surrounded by reefs in preglacial time; but in either case we may further infer that if the ocean could accomplish so much abrasion on these hard-rock extra-tropical islands as is indicated by their broad platforms, cliffs ought to have been cut on the spur ends of the hard-rock inter-tropical islands; thus the conclusion stated in an earlier section is confirmed. A fourth inference is that, inasmuch as here again the marginal depths of the banks are about 40 fathoms, the recurrence of this measure indicates that the depths are not simply the work of abrasion by the lowered ocean, but of adjustment with respect to present sea-level between aggradation by inorganic and organic deposits and degradation by waves and currents. It is worth remembering in this connection that a number of soundings on the banks report "coral."

But the assumption that the islands here considered have not subsided is without support; the evidence given above that the island of Hawaii has suffered subrecent subsidence makes it not improbable that Bird and Necker islands also have subsided. In this case the fourth inference, just stated, would be of special importance; but the problem thus becomes so largely speculative that it need not be considered further at present.

Bearing of submarine banks on the coral-reef problem.—In summarizing the considerations thus far presented, let me state explicitly that I do not wish to insist that the recent subsidence of the Ceram Sea basin demonstrates recent subsidence in the China Sea, which lies 1,500 miles to the northwest; nor that the geologically modern movements in the Philippines and other Australasian islands absolutely demand contemporaneous movements in the foundations of the Tizard and Macclesfield banks 200 or 300 miles to the west of the Philippines; nor that subsidence of the foundations of these banks, if it should be proved, would fully certify to subsidence of the great banks in the Indian Ocean also; nor that the demonstrated subsidence of all these banks would unqualifiedly require the subsidence of all the atoll foundations in

the Pacific; nor that the argument based on the dissimilarity of central depths in intertropical and extra-tropical banks is necessarily fatal to the origin of the intertropical banks by the abrasion of still-standing preglacial islands. But, on the other hand, it does seem fair to urge that the abrasion of intertropical and extra-tropical banks can hardly have taken place (if it took place at all) at the same level, because of the present differences in their central depths; that the stability of the submarine banks in the China Sea, as postulated by the glacial-control theory, is made at least improbable by the instability of the neighboring islands and sea floors; and that, if the stability of these typical banks is improbable, then the stability of all the other banks and of atolls as well is rendered very uncertain; for if one smooth bank can be produced on an unstable foundation without the aid of abrasion, then the occurrence of smooth banks elsewhere and of smooth atoll-lagoon floors is no proof of stability.

Furthermore, it seems reasonable to question the value of the often-recurring depth of 40 fathoms at the margin of submarine banks and around coral-reef slopes as an indication of a former lowered level of the ocean, and to inquire, as above, whether it may not be an adjustment of aggraded surfaces to the present level of the ocean. In view of these various uncertainties on the one hand and open possibilities on the other, it is not an inherent strength, but an easily avoided weakness, of the glacial-control theory, especially when it is applied to such banks as those of the China Sea and hence presumably when applied to atolls in general, to maintain that no important vertical movements of the earth's crust are included in the processes by which atolls are produced. We may, indeed, in view of the reasons given on page 390 for discrediting the abrasion of atolls and low volcanic islands during the glacial period, and in view of the reasons later adduced against the long-continued stability in the China Sea, make special application of the results of this inquiry by saying that the Macclesfield bank cannot be safely regarded as representing a volcanic island, once as large as Hawaii, that has stood still long enough to be worn down to low relief and that was then planed off by the glacial ocean; it much more probably represents a large atoll, formed by upgrowth during the long-continued, slow subsidence of its foundation, and recently

drowned by a rapid submergence which the postglacial rise of ocean-level may have helped to produce.

Darwin's theory of the Pacific Ocean.—After Darwin had conceived the theory of subsidence and found that it accounted for the few reefs that he had himself seen as well as for many reefs seen by other explorers, he made further test of it by inquiring whether it would account for the distribution of reefs, and wrote on this aspect of the problem in his *Journal of Researches* on the "Beagle" (1840, pp. 566, 567) as follows:

> When we consider the absence of both widely encircling [barrier] reefs and lagoon islands [atolls] in the several archipelagoes and wide areas, where there are proofs of elevation [in the form of "raised shells and corals, together with mere skirting (fringing) reefs"]; and on the other hand the converse case of the absence of such proof where reefs of those classes do occur; together with the juxtaposition of the different kinds produced by movements of the same order, and the symmetry of the whole, I think it will be difficult (even independently of the explanation it offers of the peculiar configuration of each class) to deny a great probability of this theory.

That candid statement contains the essence of a simple means of verification and serves to contradict those who later complained that Darwin had assumed that subsidence proved itself. He employed the same means of verification twenty years later in the *Origin of Species*, regarding which he wrote, "I believe in the doctrine of descent with modification, notwithstanding that this or that particular change of structure cannot be accounted for, because this doctrine groups together and explains . . . . many general phenomena of nature." Unfortunately the two additional means of verification for the theory of intermittent subsidence as provided by embayed shore lines and unconformable contacts were not used by its author, but that aspect of the problem need not be further considered here.

The occurrence of fringes, barriers, and atolls was more fully discussed in Darwin's book on *The Structure and Distribution of Coral Reefs* (1842); here an appendix of 50 pages presents a summary of all records then available, the results of which were shown upon a map; and it was these results that led to certain generalizations as to broad areas of subsidence and of elevation in the Pacific which later observations have not confirmed. Darwin did not "venture to hope that the map is free from many errors," as he had to seek "information from all kinds of sources," but he trusted that

the map would "give an approximately correct view of the general distribution of coral reefs over the whole world" (123). He added: "We may therefore conceive that the proximity in the same areas of the two classes of reefs [barriers and atolls], which owe their origin to the subsidence of the earth's crust and their separation from those [fringing reefs] formed during its stationary or rising condition, holds good to the full extent which might have been anticipated by our theory" (125). Thus encouraged he constructed a theory regarding the movements of continents and ocean bottoms out of his theory of coral reefs: "The eastern and western boundaries of our map are continents, and they are rising areas: the central spaces of the great Indian and Pacific oceans are mostly subsiding; between them, north of Australia, lies the most broken land on the globe, and there the rising parts are surrounded and penetrated by areas of subsidence" (143).

The facts of reef distribution as now reported are much more complicated than they appeared to be in 1842. For example, Darwin knew the Fiji group only as containing sea-level barrier reefs and atolls, and therefore charted it as indicating simple subsidence. Dana also interpreted the Fiji group in this way. Since those earlier years many high-standing reefs have been found in Fiji, and certain observers thereupon completely reversed the previous opinion and regarded Fiji as an area of simple elevation and as therefore contradicting Darwin's theory. Closer study gives abundant evidence to show that Fiji is really an area of complicated oscillation, and that its reefs—those now uplifted as well as those still at sea-level—were formed during times of submergence, apparently the result of subsidence. The latest statement to this effect is an article by Foye, cited above, concerning the eastern part of Fiji.

In view of the interesting complications thus brought forward, it has been said that, while the irregular uplifts and subsidences in Fiji support Darwin's coral-reef theory, they "negative the idea of a general depression of the Pacific islands, a further conception of the theory." This seems to me unwarrantably to condemn the subsidence theory of coral reefs. The simple theory of the general subsidence of the Pacific Ocean bottom was based on a belief regarding the subsidence of many Pacific islands, and is not an essential part of the subsidence theory of coral reefs; the theory of the

Pacific was a supplementary idea which now proves to be erroneous because it was based on faulty or incomplete observations quoted by Darwin from the reports of other explorers.

Darwin's coral-reef theory itself simply postulates that reefs are formed by upgrowth, whenever and wherever fitting foundations in an ocean of proper temperature subside at a proper rate. This theory now needs subordinate modification by compounding the periodic changes of ocean-level during the glacial period with the changes due to subsidence and elevation; but the theory needs no change because Fiji is shown not to be an area of simple subsidence; indeed the theory is more strongly supported than ever, now that it is found to hold good, not only for areas of simple subsidence, but for an area of complicated oscillation such as Fiji proves to be.

It is only the over-simple supplementary theory regarding the Pacific that is negatived by the new observations; that theory must be replaced by a newer and more complicated theory of the Pacific, which may well include relatively local subsidence of active or recently active volcanoes, as intimated in an earlier section, as well as ocean-floor deformation of any kind, local or widespread, dependent or independent of volcanic action; but such a theory of the Pacific does not demand any modification whatever in the theory of reef upgrowth on slowly or intermittently subsiding foundations; for, as Darwin put it, "during a gradual subsidence the corals would be favorably circumstanced for building up their solid frameworks and reaching the surface, as island after island disappeared" (94), to whatever process the subsidence might be due. That elastic theory, with its various special adaptations to special conditions as stated by Darwin, and modified as need be by combining changes of ocean-level with subsidence of reef foundations, still seems to me to give a better explanation than any other for the various and complicated phenomena of coral reefs. Molengraaff's recent suggestion[1] that the subsidence, which determined the formation of most atolls, has resulted from the local and isostatic sinking of their volcanic foundations is an important contribution to the problem, which I have briefly considered elsewhere.[2]

[1] "The Coral Reef Problem and Isostasy," *Proc. k. Akad. Wet. Amsterdam*, XIX (1916), 610–27.

[2] "The Isostatic Subsidence of Volcanic Islands," *Proc. Nat. Acad. Sci.*, III (1917) 649–54.

THE IRON-FORMATION ON BELCHER ISLANDS, HUDSON BAY, WITH SPECIAL REFERENCE TO ITS ORIGIN AND ITS ASSOCIATED ALGAL LIMESTONES

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CONTENTS

LOCATION AND AREA OF THE ISLANDS

The Belcher Islands have been until recently but little known outside of Hudson Bay, although for decades considerable trade has been carried on between the trading-posts on the bay and the Eskimos living on these islands. On most modern maps the "North Belchers" and "South Belchers" are indicated by small dots, while one chart shows a sounding of several fathoms which would probably fall on the main island. The old map prepared from Sir Henry Hudson's notes is more nearly correct in indicating the size of this land mass than any which has since been published.

These islands recently have been brought to the attention of the public through the work of the Sir William Mackenzie Expedition to Hudson Bay and Straits. This expedition was in charge of Mr. R. J. Flaherty, and to him credit is due for the accompanying outline map (Fig. 1), as minor changes only have been made in his original copy. Although this map is the result of a reconnaissance survey, it serves as a basis for travel and outlines the larger features of the land masses.

On account of the discovery, by Mr. Flaherty, of large bodies of jasper, the writer visited the islands in the summer of 1916 for the purpose of reporting on the commercial value of the iron deposits. This is believed to have been the first visit to this district by a geologist, and it is owing to the kindness of Sir William

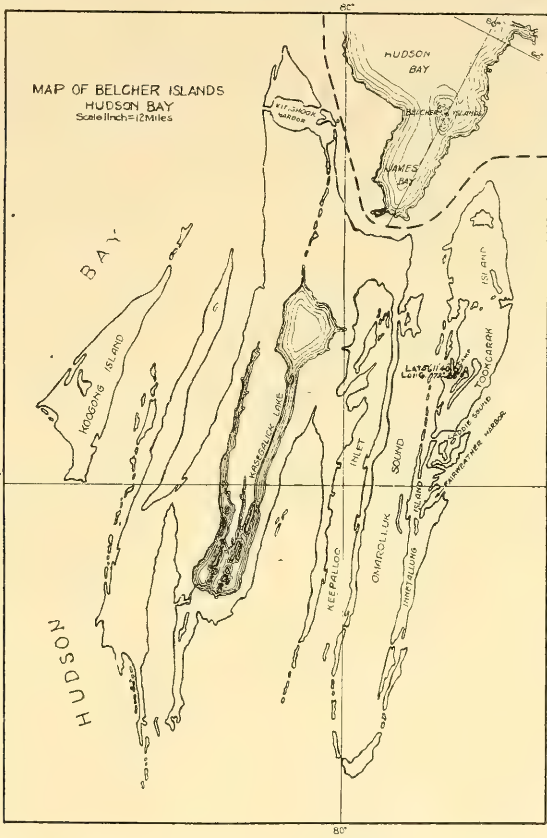


FIG. 1.—Outline map of the Belcher Islands, Hudson Bay

Mackenzie, who has granted permission to publish it, that this geological report is presented.

The Belchers, which contain a number of large islands, apparently form one large group rather than two small ones. The group is over ninety miles long and nearly sixty miles broad, and its eastern border lies about seventy miles northwestward from the mouth of

Great Whale River, on the southeast coast of Hudson Bay. Its latitude and longitude, as indicated on the outline map, were determined from astronomic observations made by Mr. Howard, a surveyor accompanying the expedition. There would be many good harbors on the islands if the bays and sounds were charted.

TOPOGRAPHY

The main physiographic features of these islands are long, narrow, more or less rounded ridges separated by sounds which are in few places more than two or three miles wide. These linear features are due to the fact that the islands are made up of a folded series of igneous and sedimentary rocks which have weathered so that the sea has entered upon the land where the less resistant beds have been eroded away. The relief, as in most other pre-Cambrian regions, is not great, the highest point so far recognized being only 450 feet above sea-level. This point is located on the large basalt hill near the center of Tookcarak Island. Few elevations have an altitude of more than 250 feet, and the land presents a worn, glaciated surface, in most places absolutely devoid of vegetation and entirely without trees. This lack of vegetation on all surfaces except on low, drift-covered areas seems to be due, not only to a complete scouring of the rocks in Pleistocene time, thus removing all soil, but also to the ice which forms on these rocks during the severe winters of the present day. There must be considerable local slipping of ice over these smooth rocks when the spring thaws come.

The occurrence of poorly developed gravel and bowlder beaches, which seem to reach as high as the highest point on the islands, is an interesting relic of Pleistocene time. It is probable that the Belchers were completely submerged during the period following the ice invasion and before the uplift of the whole Labrador Peninsula.

A rather peculiar topographic feature was observed on the basalt hill on Tookcarak Island. On this hill piles of rock were found, varying from 3 to 8 feet in height and from 7 to 15 feet in diameter. These piles are roughly conical in shape, with a depression in the top, and their shape first suggested a possible artificial

origin—some sort of mound constructed by natives. However, the finding of the fragments of a quartz vein, which had cut the basalt strewn across the pile in a straight line, showed that without doubt the blocks had been heaved up by the frost. The hollow in the top is due to the expansion of the ice forming in the depression, thus crowding the rock outward and upward.

GEOLOGICAL FORMATIONS

The islands are made up of a thick series of interbedded igneous rocks and sediments. To the group of sediments the name Belcher series has been applied, and the igneous rocks have been designated the Tookcarak diabase and basalt because of the fine exposures of these rocks on the island of that name.

There is a close relationship between these formations and those on the Nastapoka Islands and in Richmond Gulf, already described by Low[1] and Leith,[2] and they represent deposits of the same system made farther offshore. There is also a very marked resemblance between them and the Animikie and Keweenawan formations of the Lake Superior region. The following stratigraphic section may be taken as typical of the thickness and character of the Belcher series and the associated igneous rocks in the eastern part of the islands:

	Feet
1. Flow of basalt, ellipsoidal and amygdaloidal	230+
2. Iron-formation consisting of jaspilite, chert, cherty-iron-carbonate, greenalite, hematite, magnetite, and shale	450
3. Pink, white, and gray coarse-grained quartzite with bands of coarse brown sandstone and arenaceous limestone	512
4. Coarse brown sandstone and arenaceous limestone interbedded with pink and white quartzite grading into bands of gray schist and slate	2,394
5. Diabase sill	8
6. Gray, green, red, and white very distinctly banded slate and shale varying from calcareous to siliceous and locally containing perhaps 25 per cent of iron	910

[1] A. P. Low, "Geology and Physical Character of the Nastapoka Islands, Hudson Bay," *Ann. Rept. Geol. Surv. of Canada*, XIII (1903), Part DD.

[2] C. K. Leith, "An Algonkian Basin in Hudson Bay," *Economic Geology*, V (1910), 227–46.

		FEET
7.	Whitish to brownish calcareous quartzite varying from very fine-grained and cherty to coarse-grained, and grading into black quartzitic slate near the diabase	477
8.	Diabase sill	80
9.	Interbedded, dark, slaty quartzite, graywacke and shale containing considerable lime and usually highly silicified	352
10.	Silicified, crystalline limestone and dolomite interbedded with bands of calcareous red shale	151
11.	Thin-bedded, "ribboned" shales, highly banded in red, white, and gray. These are not uniformly siliceous, and they weather so as to produce striking corrugated surfaces	89
12.	Diabase dike	12
13.	Calcareous and siliceous slate	25
14.	Algal, concretionary limestone silicified and marbleized	428
15.	Diabase sill carrying much disseminated pyrite	190
16.	Mostly drift-covered, but outcrops show dense, gray, banded, siliceous, impure limestone and dolomite altered to talcose schist and serpentine near diabase	2,673
17.	Reddish to gray graywacke and arkose with narrow bands of jasper, shale, and sandstone	618
18.	Great mass of basalt and diabase forming the central mass of Tookcarak Island. The lowest rock recognized in the region and its thickness is uncertain, although it must be considerable. It is not certain whether it is an intrusion or a flow interbedded with the sediments	(?)
	Total thickness of the section	9,599+
	Total thickness of the Belcher sedimentary series	9,079+

The formations of this series, which can be correlated with some degree of accuracy with those of the Nastapoka and Richmond groups, are the iron-formation and the algal limestones. In the section on the Nastapoka Islands, Low does not recognize an erosion unconformity, while Leith considers that there is one between the Nastapoka and Richmond groups. In the section given above, the Richmond group is but poorly represented, but from Leith's description it would appear that the dividing line should be drawn at the bottom of division No. 16. The only evidence of an unconformity observed by the writer was in a narrow band, of about five feet, of fine-grained conglomerate and coarse sandstone containing little fragments of chert and jasper. This is near the base of the algal limestones on the east side of the diabase on Tookcarak Island.

This algal limestone is also well exposed on the mainland just north of the mouth of Great Whale River, where it lies directly on the Laurentian granites.

GEOLOGICAL STRUCTURE

The structure of the islands is, on the whole, simple. The rocks have been folded into large pitching anticlines and synclines, with dips varying from 75° to almost zero and with comparatively few minor folds. The heavy, igneous flows and sills have had some influence on the control of the structure, as seen in the accompanying structure section (Fig. 2). The general strike is nearly north and south, showing that these rocks were squeezed up against the land mass along the eastern side of the basin in which they were deposited, probably because of a settling of the central portion of the Hudson Bay basin. They are more steeply folded than the rocks which occur along the coast of Hudson Bay, from Cape Jones beyond Richmond Gulf, and which form the chain of islands skirting the shore in that region.

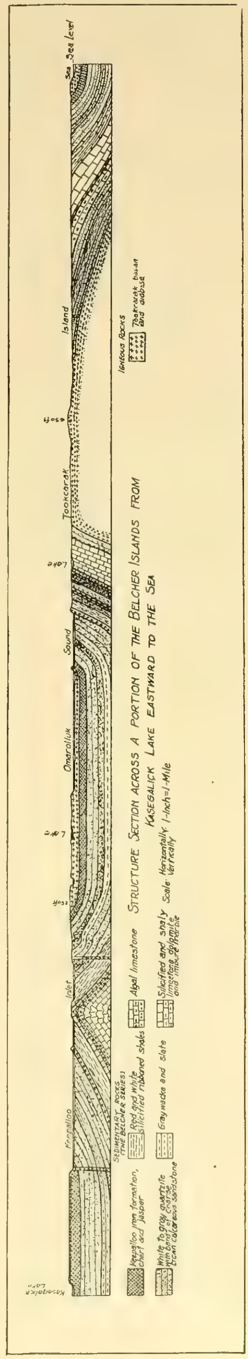


Fig. 2.—Geological structure section across a portion of the Belcher Islands

THE IGNEOUS ROCKS

The Tookcarak diabase and basalt bear a remarkable resemblance to the Keweenawan basic rocks of the Lake Superior region. Like those rocks, they are extremely monotonous in texture and composition. In some places they carry an abundance of pyrite, and

more rarely chalcopyrite is found. In one large sill a mass of impure dolomite has been inclosed, partly altered to talc and serpentine and impregnated with chalcopyrite. There is not sufficient copper, however, to be of economic interest.

The occurrence of cobalt in a calcite vein in one of these sills is interesting because of its frequent association with the Keweenawan diabases in other parts of Canada. A narrow vein of calcite was found cutting the basalt and carrying smaltite, chalcopyrite, magnetite, actinolite, and specular hematite.

The relation between the igneous rocks and the sediments is not always clear. In most cases it is quite evident that the former are distinctly later than the latter, but in the case of the large mass of diabase and basalt forming the backbone of Tookcarak Island the evidence is inconclusive. It would appear that the sediments above it have been metamorphosed to some extent, but this cannot be proved to be the result of contact action.

There are some amygdules of chlorite in its upper portion, but no sign was seen of ellipsoids, so common in some of the distinct flows in the area. Although amygdules are usually considered evidence of extrusion, they cannot be taken as definite evidence of such origin because vesicular dikes and sills are known which must have solidified thousands of feet below the surface. The question of whether an intrusive rock will be amygdaloidal or not depends chiefly upon the porosity of the rock adjoining it, and on the amount and pressure of the gases which it contains. Leith regards some of the sheets in the Richmond Gulf region as flows, but so far the writer has not found any of these interbedded igneous masses which he is sure are flows. There is one great extrusion, however, which is the youngest consolidated rock seen on the Belcher Islands, and which apparently at one time spread over the whole of the islands. It seems probable that it also extended to the Manitounick Islands near the coast of the bay. It immediately overlies the main band of iron-formation at almost every point where it outcrops. Its thickness is uncertain, since the flow is largely under water, but it is doubtless several hundred feet. Near Kasegalick Lake it is about 30 feet, but this does not represent its maximum thickness, since it has suffered much from erosion (Figs. 3, 4, 5). This extru-

sive mass consists of more than one flow, because in some places the surface of contact between two flows may be traced for a long distance (Fig. 6). Ellipsoidal and amygdaloidal structures are

FIG. 3.—View of Innetallung Island showing in the foreground the limestones and quartzites and in the distance the white quartzite overlain by the iron-formation and it in turn by the great basalt flow.

FIG. 4.—The great basalt flow overlying cherty shales and jaspilite on the shore of Kasegalick Lake.

well developed at almost every place where the surface of the basalt is exposed (Fig. 7). Outside of these two bodies all the igneous rock seen showed definite evidence of intrusive origin.

There does not appear to be any definite relation between the origin of the iron-formation and these igneous rocks, because it does not seem to matter whether they intrude it or are flows overlying it, whether they are close to it or are far removed from it. There is in many places a little micaceous and specular hematite near the contact between the diabase and the adjacent sediments, but this seems to be independent of the original iron-formation.

Fig. 5.—Large diabase dike cutting the jaspilite near Kasegalick Lake. It apparently served as a feeder for the large flow shown in Fig. 4, since the flow lies over the jaspilite just beyond the upper left-hand corner of the picture.

THE ALGAL CONCRETIONARY LIMESTONES

In recent years much attention has been paid to the study of the minute organisms which play an important rôle as precipitating agents in calcareous and iron-bearing solutions. It has been proved that low forms of plants, chiefly the algae, are at the present day causing to be precipitated great quantities of calcium carbonate in streams, lakes, and seas, and that the iron bacteria are responsible for the deposition of much iron in bogs and other bodies of water. Dr. Walcott set a new record when he described the numerous algal structures from the pre-Cambrian rocks of Mon-

tana,[1] and it now seems certain that these low forms of life flourished well back into pre-Cambrian time, and that they were

FIG. 6.—The great basalt flows forming Keepalloo Peninsula. The contact between two thick flows may be seen near the foot of the hump in the center of the photograph.

FIG. 7.—Ellipsoidal structure which is very common in the basalt flows

responsible for the precipitation of large bodies of calcareous matter whose origin was formerly a matter of doubt.

[1] C. D. Walcott, "Pre-Cambrian Algonkian Algal Flora," *Smithsonian Miscellaneous Collections*, Publication No. 2271 (July 22, 1914), pp. 77–156, Pls. 4–23.

On visiting the Belcher Islands the writer was impressed by the extraordinary development of structures which seemed to resemble so strongly the cryptozoons of the Upper Cambrian that they were at first regarded as species of that fossil. However, there seemed to be some marked differences between the two types, and the Belcher Islands specimens should be regarded as deposits made by a new group of algae. These fossils have an important bearing on the age of the associated rocks, because if they be regarded as cryptozoons we must either change the generally accepted

FIG. 8.—"Ribboned" ferruginous shale more highly silicified in alternate layers, Tookcarak Island.

conclusion that these rocks are pre-Cambrian or we must push the cryptozoons back into the pre-Cambrian. There is no definite evidence that the sediments on the east coast of Hudson Bay are pre-Cambrian, but there is as much evidence as there is for the age determination of most of our pre-Cambrian rocks of Northern Canada. Leith[1] points out the remarkable resemblance between them and the Animikie of the Lake Superior region, and Low,[2] after considering them as Cambrian and then as Laurentian, finally concluded that they were more like the later pre-Cambrian.

[1] C. K. Leith, *op. cit.*, p. 233.

[2] A. P. Low, *op. cit.*

Low had observed the concretionary structures mentioned above, and he states regarding the rocks associated with them: "No fossils have as yet been discovered in any of the beds of this formation, but the presence of certain concretionary forms in its limestones and the amount of carbon in many of the shales lead to the belief that at least low forms of life existed at the time these rocks were deposited."[1] Leith also mentions them, in the Richmond Gulf region, as follows: "The limestone floor has great concretionary structures up to two feet in diameter, the sides of the concretions locally open on one side and locally opening out into waved and crenulated bedding lines, interpretation of which the writer does not attempt, but which probably tell of conditions which if known would indicate the depth of water and other significant conditions of their formation."[2]

On the Belcher Islands these bodies form whole reefs in the more or less silicified limestone of the Belcher series, making up a thickness of over 400 feet (Figs. 9, 10, 11, 12). There appear to be two types, one smaller than the other, but as to whether these should be classed as distinct forms or simply regarded as concretions in different stages of maturity is not yet settled. The fact that the smaller ones form a large, reeflike mass near the top of the algal limestone and near the line where the rocks change in character suggests that they are incompletely developed specimens of the larger type. Both types are spherical to subspherical bodies consisting of concentric layers, and they vary in size from an inch to over fifteen inches in diameter. The larger type is seldom less than four inches, and the smaller seldom more than four inches, in diameter. The larger ones are more regular in form, being much more nearly spherical than the smaller ones, and they also show the concentric lines of growth more distinctly than the smaller ones, which show a tendency to be rather disk-shaped. The distinctly crenulated character of Cryptozoon proliferum is not found in many of these specimens. They are probably more like Cryptozoon steeli.

The concretions consist chiefly of calcium carbonate and can be almost entirely dissolved in cold hydrochloric acid. There is,

[1] A. P. Low, *Geol. Sur. of Canada Ann. Rept.*, XIII, Part D, p. 46D.

[2] C. K. Leith, *op. cit.*, p. 240.

however, some silica in small grains of various sizes, some chalcedony infiltrated along the lines between the bodies, and in some

FIG. 9.—The algal concretionary limestones on Tookcarak Island. The largest concretion is about 15 inches in diameter.

FIG. 10.—Algal concretionary limestone on Tookcarak Island. The largest concretion is 14 inches in diameter.

places a little carbon may be found under the microscope, especially along the surface separating the concentric rings of growth. This

carbon is left on dissolving the rock in cold or hot acid. No definite cell structure can be recognized in this carbon, but in

FIG. 11.—Another view of the large type of algal concretions

FIG. 12.—The smaller type of algal concretions in the limestone on Tookcarak Island.

some of the granules in the calcareous beds of the iron-formation, a little higher up in the series, grains of iron oxide, now replacing the calcareous matter, show such a distribution, size, and

arrangement that they seem to indicate the replacement of organic cells.

That these larger concretions are the result of the action of algae, which cause precipitation of calcium carbonate owing to the chemical changes produced in the water by them, there seems to be little doubt. They are very similar to the concretions described from the Algonkian rocks of Montana by Walcott,[1] and the calcareous concretions described by Roddy[2] as now forming in the streams of Lancaster County, Pennsylvania (Fig. 13). Numerous

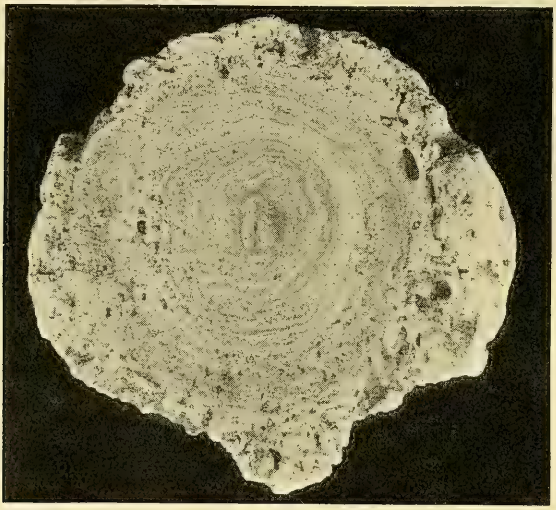


FIG. 13.—Recent algal concretion collected by J. Roddy in Conestoga Creek. Lancaster County, Pennsylvania (2.5 inches in diameter).

other occurrences of similar deposits have been described by other writers. The two types, large and small, bear certain resemblances to Walcott's *Newlandia concentrica* and *Collenia? frequens*, but they do not seem to be identical with them, and new generic and specific names should be applied.

As stated above, no definite organic cell structure has so far been recognized in these large concretions, but the replacement

[1] C. D. Walcott, *op. cit.*

[2] H. J. Roddy, "Concretions in Streams Formed by the Agency of Blue-Green Algae and Related Plants," *Proc. Amer. Phil. Soc.*, LIV, No. 218 (August, 1915), pp. 246–58.

of calcium carbonate by iron oxide in some small concretions in this same series of rocks was so suggestive that the attention of Dr. J. Ben Hill, of the department of botany, Pennsylvania State College, was called to them. Dr. Hill very kindly examined them, prepared the accompanying camera lucida sketches (Fig. 14), and the following statement regarding these bodies:

The specimens in question are generally smaller than the living Cyanophyceae, but are not smaller than the smallest of the living species. In fact, the most striking specimens are well above the lower range of size in the living species. The measurements of the *objects* in the rocks range from 0.5 to 2.5 microns for the smaller forms to 5 and 10 microns for the larger. This is exclusive of the very minute and the very large ones. The shapes of the objects would suggest species in the two classes (Coccogoneae and Hormogoneae). The isolated spherical forms resemble some genera of the Coccogoneae as *Chrococcus* or *Gleocopsa*, and the specimens showing cell-like structures connected to form a filament, some genera of the Hormogoneae as *Nostoc* or *Anoheana*.

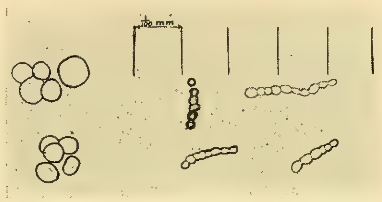


FIG. 14.—Camera-lucida drawings by J. B. Hill of grains of iron oxide resembling replacements of algal cell structurès. The accompanying scale indicates the diameter of these bodies.

Although Dr. Hill and the writer both recognized the great difficulty in distinguishing small mineral grains, which often form strings and bunches, from organic structures we feel satisfied that the sizes, shapes, and arrangement are too regular to be the result of simple replacement without some original organic control. A further discussion of these smaller concretions will be found in the section on the iron-formation.

The photographs, thin sections, and two specimens of the concretions were later sent to Dr. M. A. Howe, of the New York Botanical Gardens, and to him the writer is indebted for his kindness in making an examination of these materials. Regarding them Dr. Howe makes the following statement:

This Hudson Bay limestone is of obviously organic origin, and the organisms contributing to its upbuilding are, it seems to me, in all probability of a vegetal and algal rather than animal nature, though the microscopic structure

shows little or nothing that would justify a student of the recent algae in referring them to a modern genus, family, or class. I infer that the main organism deserves comparison with *Cryptozoon proliferum Hall* from Saratoga, New York, and one photograph is a bit suggestive of Walcott's *Collenia? frequens* as shown in his Plate 10, Fig. 3. Unless more definite structure is revealed by future sectioning it seems to me that about as far as we can safely go with these Hudson Bay fossils is to say that they are *probable* algae.

Another structural feature in the limestones of the Belcher series, and one which may also depend upon organic agencies for its origin, is a remarkably regular and uniform banding, which

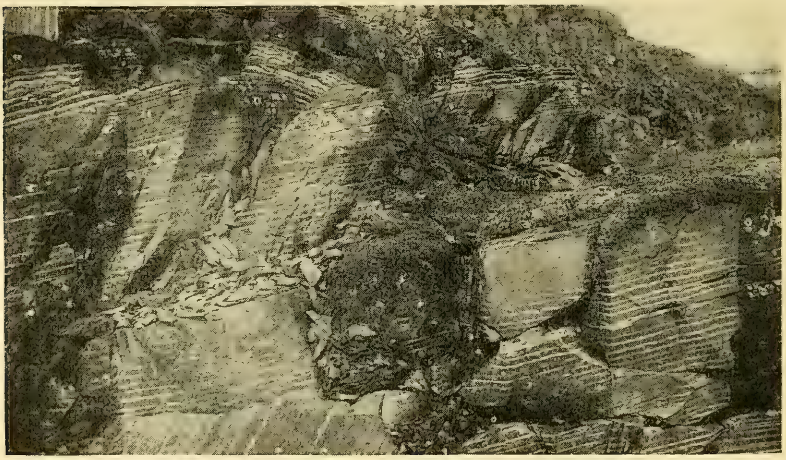


FIG. 15.—Very distinctly banded limestone on Innetallung Island. It is believed that the regularity of this banding may be due in some way to the action of algae.

is due to alternating very fine-grained and coarser-grained layers of limestone, more or less silicified, especially along the bedding planes (Fig. 15). As seen under the microscope some very small fragments of twinned feldspar scattered through the fine-grained layers and grains of quartz are fairly common. In the hand specimen the rock looks more like a cherty quartzite than a limestone, it is so dense and fine-grained. The alternate bands weather more rapidly, producing a ribbed effect. The bands are often extremely regular for considerable distances and usually run from one-half inch to three-quarters of an inch in width. It is suggested that this banding may be due to the seasonal work of low forms of life

causing variations in the nature of the deposits made during the different seasons of the year.

THE KEEPALLOO IRON-FORMATION

The term iron-formation is used here as in other writings on pre-Cambrian geology for a group of rocks which vary considerably in composition, but which together contain conspicuously more iron than their associated rocks, and which by natural concentration processes are capable of giving rise to iron-ore deposits.

There is a large body of this formation on the Belcher Islands, and the term Keepalloo has been applied as a local name for it, since it is so well exposed on the peninsula along Keepalloo Sound. It consists of jaspilite, iron carbonate, calcite, probably iron-magnesium carbonate, hematite, magnetite, chert, and greenalite. A section on Keepalloo Peninsula from the quartzite up to the basalt is as follows:

	FEET
a) A mixture of cherty, sandy, jaspery, calcareous granular rock with bands of brownish-weathering shale	54
b) Reddish and brownish fissile shale	17
c) Jaspilite	30
d) Jaspilite with bands of hematite ore	39
e) Jaspilite	46
f) Jasper and bands of lean, hematite ore	10
g) Dull, shaly jasper with bands of bright-red jasper, resembling a felsite and containing cubes of pyrite	43
Total	239

In many of these rocks small granules may be recognized with the naked eye, and they occur mostly in those rocks poorer in iron, lying near the top and bottom of the iron-formation. Their greater abundance in these rocks is no doubt due to the fact that the iron oxides lend themselves less favorably to the preservation of such structures than silica or carbonates, where there is considerable concentration of iron, and also to the fact that when a great deal of replacement occurs original structures are likely to be lost.

A number of thin sections from these rocks were studied, and it was found that in nearly all cases the rocks are made up of granules of various types. A thin section of the red jasper overlying the quartzite and lying near the base of the iron-formation

showed dirty-gray granules of a variety of shapes having a maximum size of 1.90 by 1.0 millimeters. They consist of calcite, chert, and iron oxide, the latter as a rule distributed in fine specks through the granules in an unusual manner indicating a probable replacement of organic tissues. It was in this section that the minute algae-like cells, previously described, were found (Fig. 16). Numerous veinlets of quartz following lines of fracture-cleavage indicate the extensive transfer of silica since these rocks were consolidated. These granules indicate a replacement of calcareous granules, in most places at least.

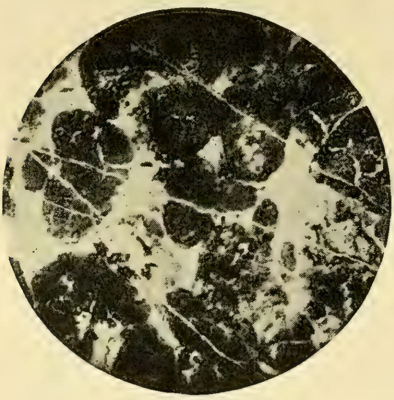


Fig. 16

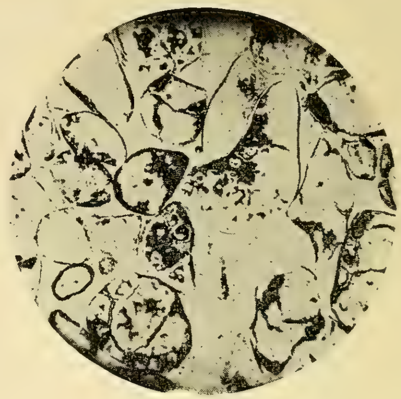


Fig. 17

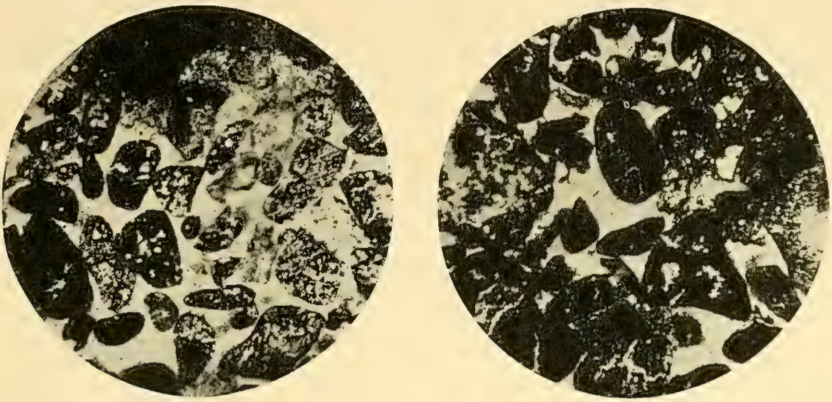
Fig. 16.—Photomicrograph of granules from the iron formation. These consist of hematite, calcite, and silica, and the groundmass is mostly silica. From these granules the camera-lucida drawings were prepared (×20).

Fig. 17.—Photomicrograph of granules consisting chiefly of silica in which some hematite and magnetite occur, the lighter areas being silica (×20). From the cherty iron formation.

Similar granules in a cherty matrix and carrying considerable magnetite were found in the rock described under *g*) in the section and spoken of as felsitic in appearance.

Another specimen of red jasper with specks of gray opal-like silica was taken from one of the bright-red bands in the iron-formation. It was found to consist of granules of fine-grained chert, opal, and iron oxide. They show a great variety of shapes varying from ovoid, balloon-shaped, ham-shaped, and roughly

triangular to nearly spherical. A few are long and narrow and some are curved (Fig. 17). One measured 1.70 millimeters in diameter. Some granules consist of opal, in others the opal is changing to chert by loss of water, and the chert is in turn changing to granules of quartz by crystallization. Some granules consist chiefly of magnetite, some of hematite, and in others a smattering of both occurs throughout the silica. In a number of granules consisting chiefly of iron oxide the grains of silica are arranged in groups, so that they produce under the microscope a cell-like structure strongly



A B

FIG. 18.—A. Photomicrograph showing the hematite and greenalite granules with grains of silica distributed in a cell-like arrangement. The dark concretions are apple green to red and brown. The lighter areas are silica (×20). From the cherty iron-formation.

B. From the same specimen as A.

resembling what would result if a fragment of a bryozoan were replaced by iron and silica. Its regularity in so many granules is suggestive.

The most interesting specimen was taken from the siliceous shales in the upper part of the iron-formation, where they underlie the basalt on Kasegalick Lake. In the hand specimen it is a dense, grayish-black to light-gray, cherty rock containing dark, cherty grains. It weathers to a dark, brownish mass. Under the microscope it is seen to be made up almost entirely of granules of various shapes, colors, and sizes (Fig. 18, A and B). In shape they are

similar to those described in the last section, ovoid, ham-shaped, irregular, and rarely spherical. In size they vary from 0.14 to 0.91 millimeter in diameter. They are colorless, reddish brown to deep brown, and apple green. The colorless ones consist of very finely granular silica with a matrix of chert and chalcedony. A great deal of calcite is distributed through the section, and one small granule consists entirely of calcite, thus suggesting that all the granules may have been calcite originally.

The green granules vary from apple green through brownish green to dark brown, depending upon the amount of iron oxide which has developed by alteration. They show very little double refraction and no pleochroism except in some places where they are altered to little rosettes of extremely small radiating needles of what is apparently an amphibole, with higher bi-refringence than the chlorites, but lower than actinolite or grünerite. Some granules are largely altered to magnetite, and in others rhombs of limonite indicate the change of siderite to limonite. In many of them the same cell-like arrangement of the quartz grains mentioned in the last section may be seen.

It seems evident that these green granules consist of iron silicate, and of the silicates, thuringite, chamosite, and greenalite commonly found in iron-ore deposits, the characters correspond most nearly to Van Hise and Leith's description of the greenalite granules of the Mesabi Range.[1]

ORIGIN OF THE IRON-FORMATION

From the descriptions given above it is evident that we have on the Belcher Islands an unusual development of large concretions whose origin can only be attributed to organic processes. We have further hundreds of feet of rocks consisting chiefly of minute granules, some of which at least show good evidence of being of organic origin from the widespread occurrence of apparent traces of plant remains in them. If these granules be compared with certain siliceous granules in the Upper Cambrian limestones of central Pennsylvania, which grade into typical oölites, it will

[1] Van Hise and Leith, "Geology of the Lake Superior Region," *U.S. Geol. Sur. Mon.*, LII (1911), 165.

be seen that they are very similar and that these Upper Cambrian oölites are associated with abundant cryptozoon fossils. Further, if the various types of oölitic iron ores from the Clinton and Cambrian of America, from the Silurian of Europe, and from the Jurassic of France and England be examined, similar bodies will be found. In fact, so far as the writer's experience goes with slides from the iron-bearing rocks of the formations later than the pre-Cambrian, such concretionary bodies are only found in those rocks which contain other evidence of organic action.

Although the writer recognizes that low forms of life, such as algae and iron bacteria, are not essential to the formation of oölites[1] and related concretions in all cases, it seems probable that they generally serve as the agents which produce the chemical changes causing precipitation of the calcium carbonate and the iron. This action seems to be due chiefly to the removal of the carbon dioxide from the acid carbonates by the algae, and the oxidation of the iron by the iron bacteria, thus in both instances producing insoluble compounds. The occurrence of vast deposits of oölites and related concretions in certain geological formations, in some instances on different continents during the same period, is also suggestive of the influence of certain organisms which reached a high stage of development at that particular time and caused the precipitation of the iron or other salts. It may also be due to the particular conditions of erosion, which permitted a large amount of any particular kind of salt to be carried to the sea during a certain geological period.

In his monumental works on the origin of the pre-Cambrian iron ores in various parts of the continent Dr. Leith has held firmly to the belief that the bulk of the iron has been supplied directly to the sea as magmatic waters accompanying the great eruptions of basic igneous rock. He advocates this theory very strongly for the iron-formations on the east coast of Hudson Bay.[2] Although the writer readily recognizes the possibility of supplies of iron salts from this source, he cannot see that they have played a rôle at all comparable to the supplies carried into the sea, or into inland

[1] An additional note on "The Oölitic and Pisolitic Barite from the Saratoga Oil Field, Texas," *Science*, N.S., XLVI (October 5, 1917), 342.

[2] C. K. Leith, *op. cit.*, p. 241.

bodies of water, in which it seems probable that many of our pre-Cambrian deposits may have been laid down by processes of weathering. The largest known deposits of high-grade iron ore in the world, the Brazilian deposits, do not show direct relation to igneous rocks.[1] The great deposits of Lorraine, the Jurassic deposits of England, and our own Clinton ores show no direct relation to igneous eruptions. Going farther back into the pre-Cambrian rocks, it will be found that the greatest deposits of all, those of the Upper Huronian, show far less direct association with the basic igneous rocks than the smaller deposits of the Keewatin. This may be due to a large extent to the conditions of drainage, which must have been much better developed in the Huronian than in the Keewatin, if we can judge from the topographic features which are likely to have been produced during such a volcanic period as the Keewatin, and from the rocks which we now find making up the Keewatin series.[2] There would be a tendency to deposit small and isolated bodies of iron-formation in the Keewatin, which later, on erosion, might add materially to the Huronian deposits.

The problem of transportation of the silica and iron has always been a big one unless we invoke the aid of hot water and magmatic solutions. However, the work done on colloids in recent years has aided us materially toward a solution of this problem. It has been recognized by Lacroix that colloids are an important product in the weathering actions which produce laterites, and the authors of a recent paper on the origin of the Missouri cherts state that, so far as they know, silica is transported only in the colloidal form and not as a sodium silicate, since such a form dissociates to form colloidal silica.[3]

The silica set free from the decomposition of basic rocks would be almost entirely derived from the silicates, and it might be retained readily and carried in the colloidal form. The iron would

[1] E. C. Harder and R. T. Chamberlin, "Geology of Central Minas, Geras, Brazil," *Jour. of Geol.*, XXIII, 358–62, 385–404.

[2] In the recent volcanics on the island of Hawaii may be seen almost a complete imitation of the topographic features of certain uncovered Keewatin igneous areas.

[3] G. H. Cox, R. S. Dean, and V. H. Gottschalk, *Studies on the Origin of Missouri Cherts and Zinc Ores*. Bull. 2, Vol. III, School of Mines and Metallurgy, University of Missouri.

also be in the ferrous form and easily transported. It has generally been considered that practically all the silica in these pre-Cambrian iron-formations has been carried in solution, and that very little of it has been clastic sediment. Experience with many different areas of these rocks shows that there is almost invariably a great deal of quartzite, arkose, or graywacke, distinct products of weathering, associated with the iron-formation, and that these often grade into the jaspers. The distinctly clastic sediments cease, and the cryptocrystalline forms of silica take their places. It scarcely seems reasonable that the deposition of clastic siliceous sediment should be so suddenly cut off in all cases and its place taken by chemical precipitates without a great deal of silt being deposited with the chemical precipitates. While this clastic material cannot now be identified in the jasper and chert, it seems probable that it is there, but indistinguishable because of metamorphism from the finely crystallized silica which makes up the bulk of all these jaspilite formations.

Regarding the adequacy of the weathering processes to produce these deposits one has but to observe the great deposits of lateritic iron which have formed, and are continuing to form, in Cuba, India, and other warm countries to be convinced of the efficiency of the weathering process. It is evident that the weathering of iron-bearing rocks is almost constantly in operation, but it is owing to certain chemical and drainage conditions that the iron remains on the land as laterite and is not carried off to the sea or to other bodies of water.

The chemical conditions depend upon two important factors, one being the presence or absence of suitable solvents for the iron and the other the presence or absence of suitable precipitating agents which may throw the iron out of solution before it reaches the sea. That considerable iron which is left on the surface as a lateritic deposit and later washed to lower levels as a detrital deposit is carried in solution is evident from the fact that some of it takes on the concretionary form after being transported from its original location.

From a consideration of the laterites the writer believes that the weathering of the basic igneous rocks would furnish plenty of iron to form the pre-Cambrian iron-formations, and that whether

the iron will be transported or left as a residual deposit will depend, not only upon the presence of solvents for the iron, but also upon the presence or absence of precipitating agencies. He agrees with Dr. Leith, however, in not regarding the pre-Cambrian iron-formations as laterites *in situ*, although certain portions of them, especially those portions consisting largely of limonite or hematite, argillaceous materials, and silica, may very reasonably be regarded as lateritic, mechanical sediments more or less assorted. The constituents of the granular portions of the iron-formation and the iron carbonate must certainly have been carried in solution, probably as colloids, and through the aid of carbon dioxide and other agents.

In the case of the ferric and siliceous granules in the Keepalloo iron-formation the presence of calcareous granules suggests that they were the primary granules, and that the iron and silica replaced them on the floor of the body of water in which these sediments were laid down. This is the principle of deposition advocated by Cayeux[1] for some of the oölitic iron ores of France. There may also have been some primary iron-oxide and iron-silicate granules, as advocated by Hayes[2] for the Wabana ores of Newfoundland, and it seems probable that the concretionary character of the ore may be due to the action of low forms of life. The work of Harder[3] and previous writers has shown that the iron bacteria are the important agents in precipitating iron compounds. These bacteria were found by Harder to be present in almost all iron-bearing waters, Spirophyllum and Gallionella, the latter, often mentioned among the algae by previous writers, being found even in underground workings of mines to a depth of several hundred feet. Harder found further that some solutions were kept under anaërobic conditions by passing carbon dioxide through them. In some solutions ferric hydroxide was precipitated, while in others there was no precipitate. The precipitation took place from either ferrous or ferric salts by oxidation.

[1] L. Cayeux, *Les minerais de fer oölithique de France*. Ministere des Trav. Pub., Paris.

[2] A. O. Hayes, "Wabana Iron Ore of Newfoundland," *Can. Geol. Surv. Memoir 78*, Ottawa, 1915.

[3] E. C. Harder, "Iron Bacteria," *Science*, N.S., XLII, No. 1079, pp. 310–11.

In the article previously cited on the origin of the Missouri cherts[1] it has been demonstrated that the presence of carbon dioxide has a very important effect in precipitating colloidal silica in the presence of calcium carbonate, causing it to be thrown down very quickly. It would therefore appear that in the action of carbon dioxide on colloidal silica and on the processes of the iron bacteria we may have a clue to the cause of the distinct banding in some of our pre-Cambrian iron-formations, provided further studies of these rocks tend to show evidence of the wide distribution of plant life during pre-Cambrian time. The fact that living algae will furnish oxygen to the waters around them and when they decay give off a certain amount of carbon dioxide may cause some seasonal variation in the precipitation of the iron and silica, and thus give rise to the banding in some of these rocks. The distinctness of the banding may later be increased by metamorphism with recrystallization of the minerals and a certain amount of transfer of materials among the bands under the influence of chemical affinity.

SUMMARY

The Belcher Islands, which lie about seventy miles from the southeast coast of Hudson Bay, have recently been brought to the attention of geologists through the discovery on them of large areas of iron-formation. The iron-formation forms part of a thick series of sediments consisting of limestones, shales, quartzites, and graywackes, and this series is intruded by sills and overlain by flows of diabase and basalt, making up a group of rocks which in many respects strongly resemble part of the Animikie and Keweenawan formations of the Lake Superior region. The limestone of this group is, however, very unusual, since it consists of concretions varying from one inch to over fifteen inches in diameter and so strongly resembling some of the modern concretions formed by blue-green algae that there seems to be little doubt that they are of algal origin. They bear some resemblance to Cryptozoon proliferum, but differ from that fossil too much to be placed in the same genus. Their abundance indicates the presence of vast numbers of low plants in the Hudson Bay basin in pre-Cambrian

[1] G. H. Cox, R. S. Dean, and V. H. Gottschalk, *op. cit.*, pp. 9–10.

time, since it has been generally agreed among geologists who have seen the same series of rocks on the east coast of the bay that they are pre-Cambrian in age.

The iron-formation consists of jasper, chert, hematite, magnetite, siderite, and green granules regarded as the iron silicate, greenalite. The chert and hematite are also in concretionary form, and it is suggested that the algae and iron bacteria have been responsible for the precipitation of colloidal silica, hematite, and iron silicate in this granular form, in some places as a direct precipitate on the floor of the basin and in others as a replacement of the calcite granules by the iron compounds.

INTERNAL STRUCTURES OF IGNEOUS ROCKS; THEIR SIGNIFICANCE AND ORIGIN; WITH SPECIAL REFERENCE TO THE DULUTH GABBRO[1]

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INTRODUCTION

It is commonly said that igneous rocks are structureless, or of massive structure, as distinct from stratified or banded rocks of other origin. When considered in detail, however, they are known to show a number of characteristic structures. Under special conditions igneous rocks develop lithophysae, orbicules, bunchy segregations, spherulites, etc. But besides these there are a number of rock masses which show a banded structure. It is this banding which is the main subject of this paper, first as to its relation to the form of the rock mass, and later as to its origin.

Three somewhat distinguishable features give a plane structure to an igneous rock unaffected by metamorphism; they will be discussed here as banding, sheeting, and fluxion structure. Various geologists have noted these structures and combinations of them under the terms bedded, stratiform, gneissic, laminated, foliated, trachytoid, schistose, linear, streaked, platy, schlieren, layers, benches, etc.

Banding.—The banding noted in many igneous rocks is an alternation of mineralogically unlike layers or flat lenses (Figs. 1, 2, 3, and 4). The dip and strike of the bands can be estimated in many cases, but may show minor undulations and bunches. In some cases the layers are all thin, but in others they range more widely, up to a hundred feet. The line of division between bands may be sharp or gradual. The texture of one band is in most cases very little different from the textures of adjacent bands, and the

[1] Published by permission of the directors of the United States Geological Survey and the Minnesota Geological Survey. Appeared first as part of a thesis presented at Yale University.

minerals interlock across the contact. In most cases there is no great difference in the mineral constituents of the bands, but only

FIG. 1.—The banded gabbro of Duluth, Minnesota. The banding in this outcrop is about as conspicuous as in the average.

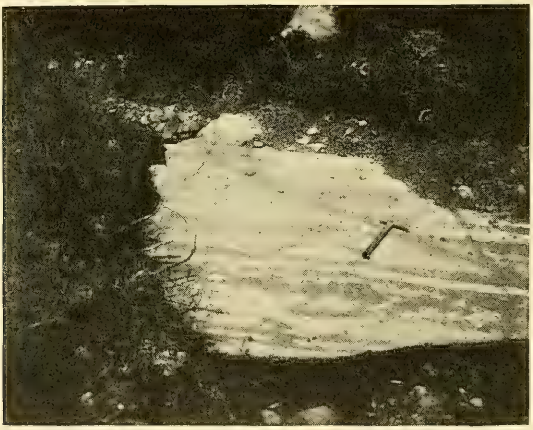

FIG. 2.—The bands in this gabbro outcrop are irregular and the color contrast is very slight, but the lighter bands are polished by glaciation.

in the relative abundance of the minerals. The colors of adjacent bands may be only slightly different, or in some cases may show a strong contrast. In a rock mass containing a variety of minerals

any one mineral may be quite completely segregated in certain bands. Where the minerals of any band weather more rapidly

FIG. 3.—Faint banding in the Duluth gabbro. These bands curve slightly, and a white band near the hammer divides to the left.

FIG. 4.—Conspicuous bands of peridotite and gabbro near the base of the Duluth gabbro.

than those of adjacent bands, such bands appear as grooves in the surface. The composition of the bands is independent of the composition of the wall rocks. There are no transverse dikes or connections between bands.

A classic example of banding is that in the gabbro mass of the Isle of Skye (1, 2).[1] There are many parallel layers of lighter and darker material, and some of the bands curve conspicuously. Another prominent case is that on Ornö (3) just south of Stockholm, where the alternate bands are black and white, and the banded rock is said to constitute the periphery of an intrusion. An equally notable color banding appears in the large igneous Ilimausak rock in Greenland (4). The bands are from one to three meters thick, and three main rock types alternate with remarkable regularity. The bands are saucer shaped in a large way and there are no apophyses between bands. Transition zones are narrow and the texture is unchanged at the contacts.

The Laurentian gneisses have a banding that is in some places clearly an original igneous structure (5). Some bands pinch out, and all are notably different from the roof in composition. There are no sharp contacts and no transverse dikes, though some related pegmatites cut across the bands. Many papers on Canadian igneous rocks mention structures of this sort (6, 7, 8). The banded rocks studied under the microscope show in the most positive manner that the structure developed while the rock was still molten, or at most only partly crystalline. There are in many specimens no traces of mineral deformation; nor is there any reason to suppose that recrystallization has obscured the signs of some previous deformation. Mount Johnson, near Montreal (9), shows bands rich in feldspathic material alternating with others richer in iron and magnesian constituents. The dip and strike can be measured. The alkali syenites of eastern Ontario (10) show bands. The Sudbury norite is reported by Mr. Hugh Roberts, of Minneapolis, on the basis of recent exploration, to show an alternation of mineralogically differing bands.

The Cortlandt series in New York has an "original gneissoid" structure in which the bands differ in mineral composition. While there are sharp contacts, it is characteristic that the grains in all cases interlock across the contact. None of the series exhibits any great amount of shearing (11). In the Adirondacks, bands one to one hundred feet thick show alternating gray and pink colors (12).

[1] Numbers refer to entries in the bibliography at the end of the paper.

In Maine some gabbro masses show alternating bands about two inches thick, in some of which segregation of feldspar produces light colors (13).

The rocks of Lizard show a linear structure and an occasional distinct banding which is said to have nothing to do with dynamometamorphism (14). Such banded rocks are reported from the Himalayas (15), the Kola Peninsula (16), and the British Isles (17, 18). In the "Cottian sequence" (19) the banding has been supposed to be metamorphic, but there are some dikes with a foliation parallel to their walls and at a high angle to the structure of the schist.

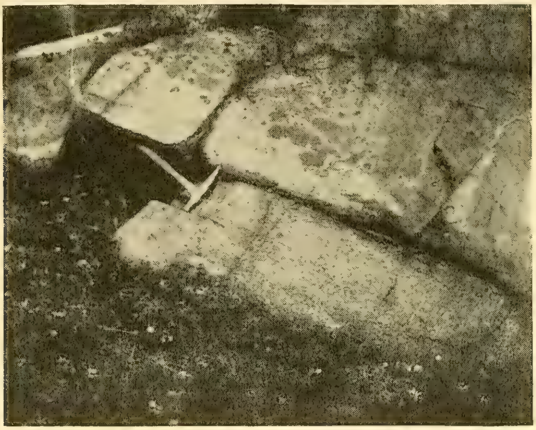

FIG. 5.—Apophyses of feldspathic Duluth gabbro into its traprock roof, east of Duluth Heights.

The banding of the Duluth gabbro was long ago mentioned (20, 21), but new work has recently been done on the area by the geologists of the Minnesota Geological Survey. The structure is exposed in typical, as well as in some exceptional, conditions at the city of Duluth. The gabbro intrusion (Fig. 5) occurred after the accumulation of a great thickness of diabase and other flows of the Keweenawan. It spread at or near the base of the flows, and along the unconformity at the base of the Keweenawan sediments a little below the flows. While the roof and floor are not an exactly continuous horizon, the transgression of a few hundred feet in a mass

a hundred miles long is insignificant. The relations are well exposed in the western part of Duluth. By detailed study it is found that the intrusion of gabbro occurred at two or more times, for at Lincoln Park and elsewhere the chilled contact and apophyses of one show that an older gabbro had already cooled. Banding (Fig. 1) is shown chiefly by the later mass, which is much the larger of the two.

In some places two rock types alternate, but in most there are several minor rock varieties in irregular alternation. The bands vary in thickness from a fraction of an inch to many feet. It is likely that in the average the gabbro does not show such minute or intimate lamination as some associated sediments,[1] but while there may be a general difference, each varies to resemble the other. Some contacts between adjacent bands are abrupt, but more commonly there is a complete gradation between them. Some neighboring bands contrast strongly in color, while others are visible only on careful scrutiny; some are intensified by weathering, producing black, brown, gray, and white colors; some are conspicuous only from a difference in the degree of glacial polish (Fig. 2). Some large outcrops at Duluth show faint bands as much as fifty feet wide. It is therefore evident that smaller outcrops a few feet wide may not reveal a banded structure even if it really exists. The whole area has been mapped as banded, because the outcrops which did not show the structure were small and not numerous; they may represent other variations of the mass, but are here considered as probably thick bands. Most of the bands are regular, parallel, and fairly continuous along the strike and dip. However, there are locally lenticular bands, and spots or bunches along the bands, as shown in Fig. 2. Rarely the bands curve and finger out into each other (Fig. 3) and are as complex in structure as the ancient metamorphic gneisses. This irregularity is not as prominent as in the gabbro of the Isle of Skye (1); but locally the average dip of about 25° to the east increases to 80° with some variation also in strike. Although these outcrops may resemble metamorphic gneisses enough to be deceptive, a thorough study of

[1] U. S. Grant, "Contact Metamorphism of a Basic Igneous Rock," *Bull. Geol. Soc. Amer.*, XI (1900), 508.

the rocks shows little trace of any crushing or recrystallization. Poikilitic and ophitic structures remain unaffected, and the minerals are fresh. The associated earlier flows and sediments show no such structure as would have developed if the gabbro had been metamorphosed. The structure is therefore a primary one.

In general, the minerals of one band are the same as those of adjacent bands, and the banding is a consequence of difference in proportions of minerals. Textural changes are slight. Rock types at Duluth range from peridotite to anorthosite as extremes, with magnetite gabbro and troctolite as other variations from normal gabbro. A few measurements were made on thin sections of bands of gabbro, and some have been selected and presented in Table I to show how the bands vary.

TABLE I

	Percentages by Weight				
	Plagioclase	Pyroxene	Olivine	Magnetite	Miscellaneous
Common bands	75	10	10	4	1
	65	19	10	5	1
	70	18	0	12	0
Two adjacent bands such as alternate many times	84	12	3	1	0
	62	15	12	11	0
Bands of extreme composition	96	3	0	1	0
	20	44	0	36	0
	49	48	0	3	0
	2	15	70	13	0
	75	2	22	1	0

Detailed observations of the dip and strike of gabbro structure at Duluth show only minor irregularities. Fig. 6 shows the general structure of the gabbro in those townships where observations have been made. It gives the impression of concordance with neighboring contacts. Magnetic mapping of the portion of the gabbro far to the northeast shows the general parallelism of bands and contacts, as well as the probably lenticular nature of the bands, which in Fig. 7 represent titaniferous magnetite ore.

It may be added that some large sills, more or less related to the gabbro (22) and typically exposed at Beaver Bay, on Lake

Superior, show an exactly similar banding. The same gabbro in Wisconsin shows what has been described as a "bedded" structure (23).

There are a number of smaller masses which also show a banding, possibly of similar origin. The Purcell sills gabbro has certain streaks of lighter color (24) in addition to the separation into differentiated zones. A gabbro dike near Boulder, Colorado, has bands of iron ore parallel to the walls (25). A dike in the Isle of Man is similarly banded (26). The Mt. Holmes bysmalith has a color banding parallel to the walls (27). Other examples will no

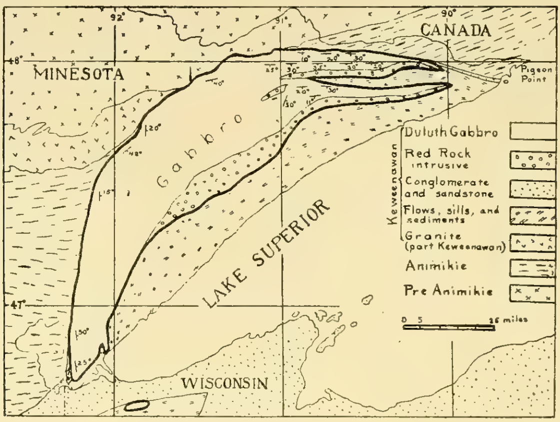

FIG. 6.—Sketch of the area of the Duluth gabbro showing the dip and strike of its internal structure.

doubt be recalled by those who have worked in igneous rocks. A color banding is visible in many flows, but the difference in mineral content of the bands is not always clear.

Fluxion structure.—Certain igneous rocks have an abundance of platy or needle-like minerals, notably the feldspars and hornblende. Many gabbros and syenites show a certain amount of parallelism of such grains (Fig. 8). Most of these rocks show banding of the sort just discussed. The rocks of Lizard (14) and the Adirondacks (12) and Laurentia (5) are "foliated." The Ilimausak (4) rock has "primary schistose structure." The Mt. Johnson rocks (9) have a "fluidal arrangement of grain." The

Ontario syenites have an "original foliated or schistose structure" (10). All of these are noted by the authors as a feature in addition to banding.

The occurrence at Duluth is a particularly good example of this structural feature as well as of the banding. Both the early, relatively thin feldspathic gabbro and the later banded gabbro show a parallelism of plagioclase grains in many outcrops. The smaller sills referred to also show the fluxion structure.

Sheet structure.—When independent of surface changes of temperature, this is probably related to some such feature as the banding and fluxion structure just described, even when they of

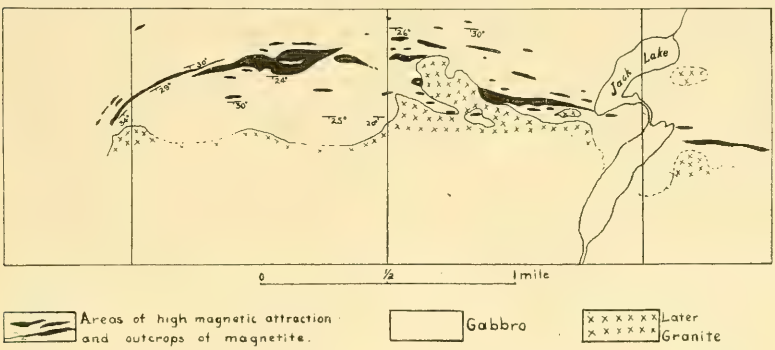

FIG. 7.—Map of three square miles in Cook County, Minnesota, showing in black the lenticular form of the outcrops of bands in the banded Duluth gabbro. In this case the bands carefully mapped are those rich in titaniferous magnetite.

themselves may be inconspicuous. Platy parting is recorded in the Ilimausak rocks (4) and the laccoliths of Highwood Mountains (28) and at Tripyramid Mountain (29) and elsewhere. The Duluth gabbro shows such joints in many outcrops (Fig. 9).

Combinations.—It is evident from the foregoing notes that several masses show two or three structural features at the same time. This is true for a single outcrop as well as for the mass as a whole.[1]

[1] The term "gneiss" may be extended to cover such rocks as these showing banding and fluxion structure, but when this is done the name should be qualified as "primary gneiss." The usage is discussed by Barlow, "Nipissing and Temiskaming Region," *Geol. Survey of Canada, Ann. Rept.*, X (1897), Part I, p. 49; and Miller, *Bull. Geol. Soc.*

A B

C D

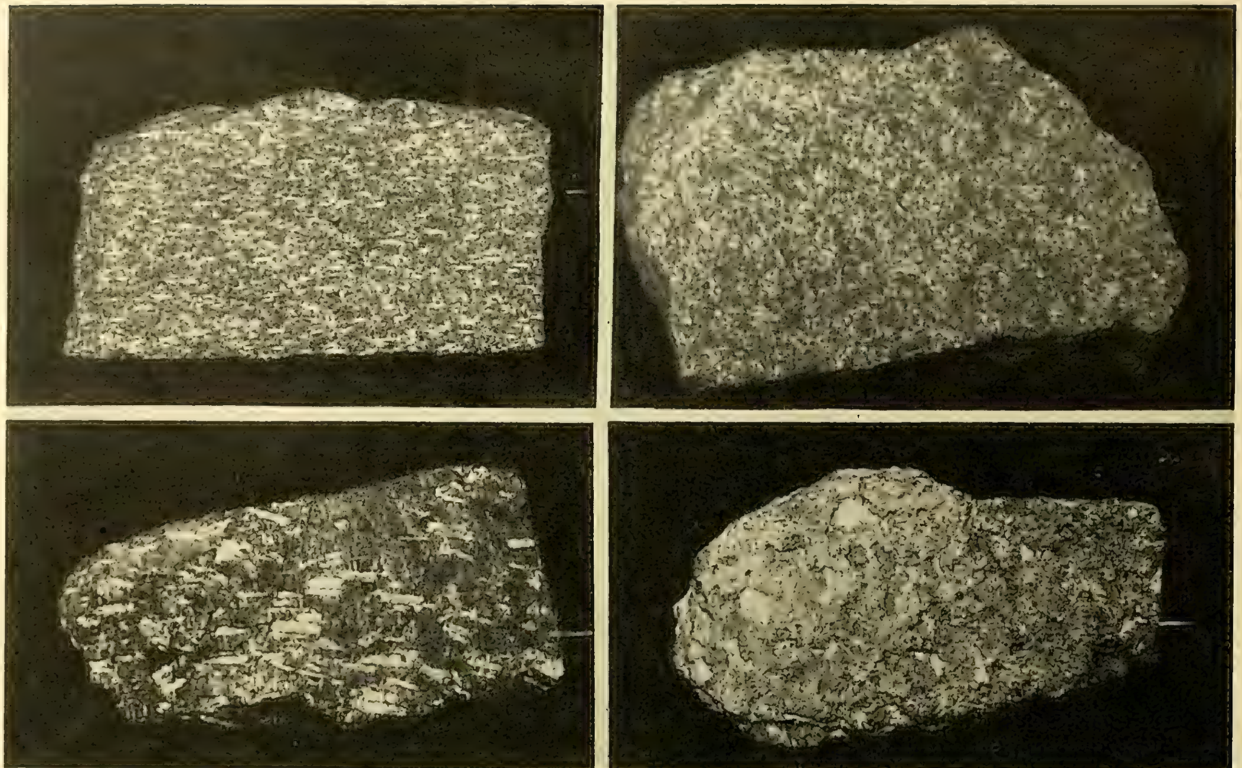

FIG. 8.—Top and side views of gabbro and a magnetite segregation in the gabbro, showing fluxion structure. About one-half natural size.

THE RELATION OF IGNEOUS STRUCTURES TO THE FORMS OF IGNEOUS MASSES

Pirsson finds the parallel arrangement of crystals and the platy parting of the laccoliths of the Highwood Mountains parallel to the roof (28), and has some evidence of a similar relation at Tripyramid Mountain (29). Iddings reports the parting and color banding of the Mt. Holmes "bysmalith" (27) parallel to the walls.

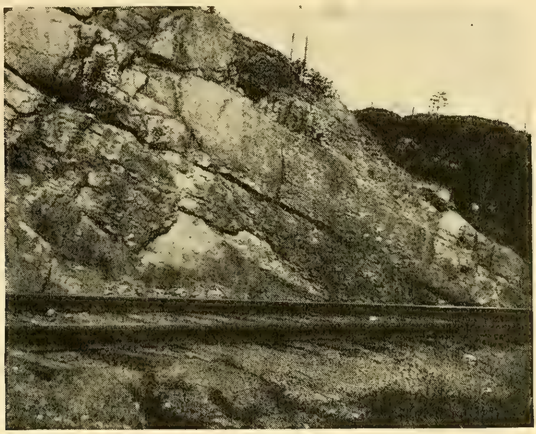

FIG. 9.—Sheeted structure in the Duluth gabbro evidently independent of the surface. Spheroidal weathering also appears.

Rogers finds that the bands in the Cortlandt gneiss bear no definite relations to the borders of the magma (11). However, banding in the Adirondacks is of several kinds, and Miller records "a foliation that boxes the compass around the borders of the stocks" (30). The banding in lava flows and their trachytic structures is often recorded as parallel to the general plane of the flow. Examples

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Amer., XXVIII, 455. "Fluidal gneiss" and "injection gneiss," as terms recently developed in structural geology, are probably best restricted to another type of structure. It is detected in tracing igneous injections in bands between masses of a schist of other cleaved rock, or even curving in and out among rock fragments. This results in an alternation of the original cleaved rock (of whatever origin) and the igneous rock. Solution of the original rock and its metamorphism by the magma may produce such an intimate intergrowth as to make distinctions between intrusive and intimate intergrowth as to make distinctions between intrusive and intruded rocks difficult. See Leith, *Structural Geology*, p. 85; and Cross, *Science*, XXIX, 946.

are seen in the Yellowstone banded obsidians (27) and the flows of the eastern (31) and southwestern states (32). The bands in the Purcell sills "approximate a position parallel to the upper and lower contacts of the sill" (24). Barlow records that the strike of the banding is uniform over large areas in the Nipissing and Temiskaming regions, and shows a "marked correspondence in direction with the line of outcrop of the neighboring stratified Huronian rocks" (8). Adams finds the banding of Mount Johnson vertical and clearly parallel to the walls of a volcanic plug curving around the mountain (9). Adams and Barlow say that the strike of the banding and foliation of the alkali syenites of eastern Ontario conforms to that of the adjacent country rock (10). Ussing considers the strata of the Ilimausak mass the upper layers of a batholith, but records that near the walls of the chamber the bands, which are nearly horizontal most of the way, turn up and become parallel to the walls (4). Gregory mentions some dikes which are foliated parallel to the walls, but not parallel to the foliation of the neighboring schists (19). Banding also appears in a dike in the Isle of Man, parallel to its walls (26). Harker says that the banding of the gabbro at Carrock Fell is parallel to "the lie of the intrusion as a whole" with only minor undulations (17). At the Isle of Skye the banding is undoubtedly related to the boundaries. Iddings says that it is "not locally referable to the form or boundary of the body of a particular igneous rock,"[1] but he cannot have seen as much of the structure as Geikie and Teall, who say that each sheet of gabbro "consists of many parallel layers . . . . which correspond in direction with the trend of the sheet itself"(1); or as Harker, who says that the bands dip with the mass as a whole and are in general parallel with the upper and lower surfaces of the sheets (2).

A similar disagreement may be recorded in the case of the Duluth gabbro, where Elftman says that the banding is irregular (21), and more recent data show only minor variations from the direction of the contacts. The agreement of strike with the boundaries of the mass is shown in Fig. 6. The agreement in vertical section is more difficult to prove, on account of the scarcity of exposures showing such vertical sections. A single outcrop at

[1] J. P. Iddings, *Igneous Rocks*, I, 252.

Duluth (in the NW. Cor. Sec. 22, T. 50. N., R. 14 W.) reveals the upper contact of the gabbro with a clear exposure of dip. The roof here dips east a trifle irregularly at an angle of about 15°. At Lincoln Park it may be seen further that the later banded gabbro dips east under the earlier feldspathic gabbro. At the base of the gabbro, where one might search for the exposures of the floor, the relations are confused by pegmatitic and aplitic emanations and differentiates of great variety. At the Paulson mine in Cook County the floor apparently consists of eroded iron formation. Though the dip of the contact is not well exposed, drilling was conducted on the assumption that the bedding of the sediment and the banding of the gabbro indicated the direction of the contact. As far as exploration went, this proved to be true.[1] A floor under the gabbro, conforming to the position of the banding, is also indicated by the constancy of the horizon of the gabbro intrusion, and by the arrangement of differentiates; some heavy segregations are on the northwest, as if a floor dipped under them on that side.

A review of literature and suggestions to be presented later with regard to the origin of these structures has no reference to any process which would tend to develop a banding independent of the boundaries. The favored theories involve movement during crystallization, and it would be expected that such movement would be more or less controlled by the boundaries of the magma chamber.

These results are sufficiently uniform—only one apparent exception—to warrant the assumption that in a large way the fluxion and banded structures, as well as sheet jointing (when not referable to surface weathering), may be a guide to the position of the boundaries of igneous masses, and therefore of great value in mapping igneous forms and interpreting their position. The occurrences include flows, dikes, sills, a plug, a bysmalith, and laccoliths. Exceptions may be found, but even if the idea proves untrustworthy it is worth stating for the sake of stimulating accurate observations and records, which are at present not very numerous.

[1] E. C. Harder, personal communication.

THE ORIGIN OF IGNEOUS BANDING

Former suggestions.—The field study of the structure of the Duluth gabbro led the writer to assume a process of convection during crystallization as its cause. On reference to the literature, it was found that Bowen recently eliminated convection from the list of magmatic phenomena which he considered important (33). No clear statement of the relation between convection and structure could be found, and a review of the various explanations of the banded structure was thought desirable. In addition to suggestions made in connection with specific areas already mentioned, there are some discussions of the phenomena in general papers (7, 33) and textbooks (34).

Banding is so characteristic of metamorphic gneisses that the structure is not rarely referred to secondary processes, but the papers cited above show very conclusively that much of it is primary. Furthermore, as igneous rocks they cannot have been fused in place and retained traces of earlier structure, for the gabbro at Duluth and banded rocks in a number of other places are known to be intrusive into both their roof and floor (Fig. 5), neither of which is much metamorphosed. Of the other possible causes of banding, the following tabulation includes the chief suggestions found:

1. Partial assimilation of inclusions, forming schlieren
2. Lit par lit, or fluidal gneiss
3. Deformation during solidification
4. Deformation just after solidification
5. Streaked differentiation, with reference to rhythmic cooling or intrusive action
6. Successive intrusions:
   a) Cooling separately and successively
   b) Cooling later, all together
7. Heterogeneous intrusion

The writer would add:

8. Convection during crystallization differentiation

Discussion.—The idea of partial assimilation of xenoliths, or lit par lit injection of wall rock as an explanation of banding, loses

its main support when it develops (as in Duluth) that the floor and roof are rocks of about the same composition as the average gabbro, and that the bands range from anorthosite to peridotite—with compositions that could hardly be synthesized from any rocks in the region. It is admitted that schlieren, developed from xenoliths, occur in some local spots, but they have no relation to the banding and show no extreme in composition.

Deformation during crystallization might explain the orientation of grains, but cannot clearly explain the banding.

The process of differentiation has not been described so as to explain the banding. It is, of course, probable that a rhythmic variation in the process of crystallization would give a rhythmic alternation of rock deposited, but that furnishes no explanation of the fluxion structure. None of the theories of differentiation outline a process that will result in a combination of gravitative arrangement, parallel banding, and parallelism of grain.

It is well said that the necessary conditions for igneous banding are heterogeneous composition and differential movement (34). Of the suggestions listed above, those which fulfil these two conditions are successive intrusion, heterogeneous intrusion, and deformation during crystallization. It is to be noted that each of these involves movement. The orientation of the platelike grains can hardly be accomplished except by some sort of movement of the magma while the plates are suspended in it. Such orientation is seen in surface flows where it is parallel to the direction of flow, and is often visible in thin sections of trachytes. To be sure, the settling of crystals, which idea is in special favor recently, might be thought of as analogous to the settling of mica plates in a sediment. Those falling on a flat bottom might adjust themselves in horizontal and parallel positions. On the contrary, it does not seem probable that such an orientation would occur in a crystallizing magma. The settling is slow, so that other crystals might lodge close to the plate and prevent its rotation. Furthermore, the difference in specific gravities, tending to orient the plates, is less than the difference for mica in water, while the viscosity opposing the rotation is much greater. As a final argument against orientation by settling, the relation of structures at Mt. Johnson (9) should

be considered. There orientation is vertical and parallel to the sides of a volcanic plug as if dragged upward by eruptions through the channels, while in other respects the structures seem to be identical with those described elsewhere. It therefore seems necessary to adopt the customary view that the orientation of grains here associated with banding is a result of magma movement during crystallization in the general direction of the grains and of the bands, i.e., parallel to the walls of the chamber. This view is so prevalent that the structure is often called "fluxion structure," even when its movement cannot otherwise be determined.

The question remains as to the nature of the movement. The common suggestions are movements of intrusion or of deformation. The writer is in favor of a third suggestion, viz., a circulatory movement. The data on which the argument is based are simple. It will be recalled that the banding of many rocks involves, not only a parallelism of grain, but an alternation—many times repeated—of mineralogically unlike bands. It is also known at Duluth that the extreme differentiates have in a large way become distributed in crudely gravitative positions, i.e., heavy near the bottom and light near the top. With these points in mind the several suggestions may be considered in detail.

Successive intrusions of slightly varying magma are undoubtedly able to produce banded rocks and may even give a crudely gravitative arrangement; but the intrusion of successive layers of alternating composition, a few inches to a few feet thick, until the whole had a thickness of thousands of feet is inconceivable. The process would have to be extremely minute and often repeated in order to explain the detail of some outcrops. But such minute intrusion can hardly account for an intrusion several miles thick, where the intrusive action must have been on a grand scale. Even a process of crystal settling of each intrusive, combined with a sequence of intrusions, does not explain the alternations that are visible in some outcrops, where dozens of alternating bands appear in as many inches.

Turning to heterogeneous intrusion, we find that the idea is accepted without any feeling of shock or surprise when attention is

called to the variety sometimes shown in a series of extrusive lava flows, apparently derived from a single large chamber. The most recent statement of the case is incidental to a discussion of differentiation by crystallization and settling (33). It is necessary to introduce some modification to explain the development of the banded structures often seen. If differentiation took place by settling of crystals, and before the mass was all solid some dynamic process squeezed the liquid out from between the settled crystals, this liquid would not be the same in composition as the supernatant magma. These two liquids might be involved in an intrusive layer and produce bands if not thoroughly mixed before crystallization. There are several difficult points in the application of this idea to such banded rocks as the Duluth gabbro, though it seems clear from the variety of the Keweewanan lava flows that differentiation was well advanced before intrusion.

First, the mechanics of the filter-pressing process in a deep reservoir like a batholith is not stated and is a little hard to conceive. Pressure on a magma is largely hydrostatic and not differential.

Secondly, if heterogeneous liquids were intruded into so large a chamber there would be a great stirring and mixing effect and plenty of time to make the mixture more homogeneous before it crystallized. In general, the larger the mass the more time available for diffusion and mixing. If banding was a result of heterogeneous intrusion, the larger masses would be least banded. As a matter of fact, the Duluth gabbro, one of the largest known intrusions, is most strikingly banded.

Thirdly, there is no reason to assume that the differentiation which caused the variation in the magma in the deep reservoir should suddenly cease upon intrusion into an upper horizon. In fact, from the gravitative arrangement it seems almost certain that some differentiation did take place. To be sure, if the heterogeneous magma varied in specific gravity, the several parts might have been intruded in roughly gravitative position; but even if they were, there was nothing to stop the differentiation until the magma cooled. In so large a mass as the Duluth gabbro there would be plenty of time for further differentiation by settling. The difficulty

arises from the fact that if a crop of crystals settled across the intrusive bands they would destroy the banding and orientation.

Fourthly, the alternation of bands found is so varied and extreme in composition—from anorthosite to peridotite—that the process of filter pressing can hardly yield the liquids which would be needed.

Finally, the alternating bands, if they represent two liquids imperfectly mixed, should consist of a large volume of the upper liquid phase and a smaller amount of the phase strained off or filter-pressed from below. At Duluth there are found small volumes of granophyr and peridotite, with large volumes of anorthosite and immense volumes of olivine gabbro. These would hardly result from filter pressing.

It thus appears that crystal settling and filter pressing and heterogeneous intrusion will not explain the structures at Duluth. However, other modifications of the idea of heterogeneous intrusion may be suggested. The objections mentioned are enough to make them all unsatisfactory. The magmas may come from two reservoirs or become heterogeneous by any other process, but if they did they would have time to mix, and the mixing and crystal settling would destroy the banding. The magmas might be intruded, when partly crystallized, as a great mass with "mushy" consistency. Banding and orientation would be satisfactorily explained by this idea, but in such a banded, mushy mass there would be no opportunity for gravitative differentiation.

It seems necessary to believe that both differentiation and some sort of motion were involved in the production of the bands, and that these occurred after the magma reached its chamber. It may be best to leave the matter open as to the kind of motion that occurred, but the idea of convection is an attractive one.

CONVECTION

It is suggested that many cases of igneous banding are related to convection currents during crystallization differentiation. It is not necessary, in conceiving of this action, to regard it as a very thorough stirring, but rather as some degree of circulation following the intrusion of either homogeneous or heterogeneous magma. Neither is the process exclusive. Successive intrusions of hetero-

geneous material probably occur, and crystal settling, differentiation, and deformation all leave their mark; but these things are apparently not sufficient to produce the structures seen. Convection currents during crystallization result in bands and aid in the differentiation. Such a circulation would drag into parallel position any crystal formed near the wall of the chamber just as it became lodged in the viscous matrix and was removed from circulation. Rhythmic effects in the way of cooling, intrusive action, or gas emanation (all of which are known to be rhythmic) might rhythmically change the mineral composition of the crystals growing along the walls, and thus result in banding. Other features also are favorable and the writer does not find the mechanics of the process at all difficult.

SUMMARY

A review of the descriptions of banding in igneous rocks and a detailed study of the Duluth gabbro show that the alternation of mineralogically unlike bands is commonly accompanied by a fluxion structure and in some places by a sheet jointing.

These structures are found to be parallel to the bounding surfaces of the igneous masses in nearly every case. Exceptions should be carefully studied and the facts in all cases noted, because such a relation of form and structure would be of great value in mapping and economic work.

The banding and related structures probably develop during crystallization, while the magma is in convection circulation.

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THE HABITAT OF THE SAUROPOD DINOSAURS

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INTRODUCTORY

In the study of the sauropod dinosaurs which has been carried on by the writer for a number of years under the direction of Professor H. F. Osborn in connection with the preparation of the latter's monograph on these reptiles, some problems have presented themselves upon which a study of the habitat, or immediate environment, has a bearing.

The course, or trend, of evolution in a group of organisms is limited, or controlled, by two things: (1) the heritage or assemblage of characters inherited from the ancestors; and (2) the environment. The environment offers the organism opportunities for developing along a limited number of lines. What these lines will be depends upon the general character of the environment. For instance, upon inland plains advanced aquatic adaptations, such as are characteristic of marine organisms, will be barred out, and under strictly marine conditions the development of cursorial locomotor apparatus is impossible. This is true no matter what may be the heritage of the organism under discussion. Within certain limits, however, the environment offers the possibilities or opportunities for evolution along a number of lines. The heritage furnishes the material or instruments by which, or by a modification of which, the organism may evolve along one or more of these lines.

In working out adaptations and habits in a group of animals such as the Sauropoda, morphology, together with comparison with living forms, will be the most important guide. Morphological structures have meanings, and if these meanings can be interpreted the habits of the animals possessing the given structures can be determined to a certain extent. A study of the environment of

the group in question may aid in interpreting the structures and may guide us in determining the habits of fossil animals, because certain types of environment definitely exclude certain modes of life, as has been noted above. The habits of the animals must have conformed to the environment which actually surrounded them when they lived.

The present discussion is concerned with the environment of the Sauropoda. The environment of a group of organisms is divisible into two components: first, the physical, and second, the biotic. These are related to each other in a complex manner, but with regard to their relation to a given group they may be considered separately. The first is concerned with such things as climate, with mountain, plain, delta, lake, or marine conditions, with the geographic extent of a given type of physical condition, with means of communication and barriers preventing communication or intermingling, with the rate of sedimentation and erosion, with the presence or absence of volcanic phenomena, etc. The second is concerned with food supply, with competition, and with enemies. If in a given case the various factors of each of these components may be determined, a comprehensive idea may be had of the habitat, or immediate environment, of the group of animals involved.

PHYSICAL ENVIRONMENT

The physical environment of the Sauropoda is concerned with the geology of the Morrison, Arundel, Wealden, and corresponding Indian, African, Patagonian, and Malagasy formations. The American Morrison may be considered in this connection as an example of sauropod-bearing deposits.

The physical characters of the Morrison, its relations to other formations, considered in connection with the general Mesozoic history of Western North America, indicate certain definite things regarding the geography, topography, climate, and dominant physical processes of the time and region in which the Western American Sauropoda lived. An extension of this study to include world-wide conditions would give a fair idea of the physical environment in general.

The characters of the Morrison may be discussed under the following heads: (1) distribution, present and probable past; (2) lithology; (3) internal structures; (4) stratigraphic relations; (5) conclusions regarding conditions of deposition, physical processes dominant during the period of deposition, and middle Mesozoic history.

1. The present distribution of the Morrison is indicated on a map compiled by the writer.[1] The formation outcrops along the eastern and western borders of the Rocky Mountains in Wyoming, Colorado, and New Mexico; in the rim of the Black Hills; in canyons in southeastern Colorado and northeastern New Mexico; around the borders of the Bighorn and Owl Creek mountains in Montana and Wyoming; in isolated uplifts in Wyoming; in canyons and mesa scarps in northwestern New Mexico, western Colorado, and eastern Utah; and in various other occurrences in the states mentioned. The outcrops are usually not extensive, the formation never being the country rock over a wide area. The total area in which Morrison outcrops occur is, however, very large. There are vast areas where the Morrison must unquestionably underlie younger formations. The areas in which the Morrison was formerly present, but from which it has been removed by erosion, are also very large, their exact size not being known at the present time. The total area which was formerly covered by Morrison sediments must have been extremely large, very likely exceeding a million square miles in extent. As remains of sauropods are now found at practically every region of Morrison outcrops, it follows that the distribution of the Sauropoda in North America was also very wide.

2. Lithologically the Morrison is composed of a variety of rock types. The formation is frequently described as a series of "joint clays," fine-grained sediments which appear to be fairly well consolidated when dry, but which crumble or break readily when wet. These are red, brown, gray, or maroon in color. Petrographically they are fine grits composed mostly of quartz, with some argillaceous interstitial material which may or may not be

[1] Charles C. Mook, "A Study of the Morrison Formation," *Annals of the New York Academy of Sciences*, XXVII (1916), 39–191, Pl. VI.

stained red by hematite, as the case may be. These grits, especially the red ones, are frequently most abundant in the upper levels of the formation; it is in these upper levels that calcareous material is more scarce. Beds of sandstone, sometimes of considerable thickness, occur at various levels; these sandstones are made up principally of quartz, which is often well rounded; feldspar grains, either fresh or more or less altered, occur along with the quartz; in some beds grains of volcanic ash, both fresh and altered, are found; and in a few instances beds of coarse sand several feet thick are made up of volcanic ash. Limestone beds, usually not over a foot or two in thickness, are frequently found in a section; these are sometimes composed largely of the shells of small gastropods. They are more common near the base of the formation than in the upper members. The lower beds are often arkosic, considerable quantities of feldspar being present, often cemented to the accompanying quartz and to each other by a calcite matrix. Thin beds of agate are found in some sections.

Very coarse material is not found in the Morrison. Sandstones of a moderate degree of coarseness are common throughout the entire area of Morrison outcrops. Such sandstones are, however, on the whole thicker and more common in the western exposures than in the eastern.

3. The Morrison contains internal structures of considerable interest. In the first place the various strata often appear to the eye to extend over considerable distances, but when detailed sections are made, even a few miles apart, and compared with each other, it is noticeable that the details of the sections vary considerably. A gradual thinning out of beds of one kind of material, and their replacement by another kind, is the rule in this formation. For all of this variation the general aspect of the formation in one locality is very much like that in another. This type of thing has been aptly described by Dr. Lee as "uniformly variable." In some cases the thinning out of beds is sudden, as in the case of the old stream channel exposed at the site of the old Marsh-Hatcher dinosaur quarry near Cañon City.

The variation and at the same time the uniformity of the thickness of the formation are of special interest. The greatest recorded

thickness is about 900 feet, and it is possible, if not probable, that beds are included in this measurement which are older than the Morrison. The range in thickness is usually from 700 feet in the western sections to less than 100 feet in the Black Hills region. This thickness is exceedingly slight for a formation of such vast geographic extent as the Morrison. In general, the western sections are thicker than the eastern, but this will not hold as an invariable rule. Sections of 400 feet or less sometimes occur in the western areas, and sections fully 400 feet thick exist in eastern New Mexico. No section of more than 500 feet is known from the eastern areas, however, and the western sections frequently reach that or a greater thickness. The Morrison sediments might perhaps be described from the point of view of thickness as a thin mantle of sandstones and clays extending over a vast area, thickest in the west and thinning out definitely, but irregularly, to the east.

Cross-bedding is abundant in the beds of the Morrison, especially in the sandstones. It is represented by the type described by Walther and others as typical of desert deposits, and also by the type usually assigned to stream deposition.

4. The stratigraphic relations of the formation are in a broad way disconformable with regard to the underlying terranes. The deposits rest upon older formations of various ages, from the Unkpapa sandstone of uppermost Jurassic or earliest Comanchean age in the Black Hills region to Archean crystallines in the Rocky Mountain region. The relation of the Morrison to the overlying sediments appears to be a conformable one. The fact that the Morrison appears to be closely related to the succeeding formations has been pointed out by Lee.[1] For further description of the Morrison formation the reader is referred to the above-mentioned article on the Morrison by the writer and to the bibliography contained therein.

Taken together, the physical characters of the Morrison indicate a history something like the following: After an extensive period of erosion, during Jurassic and perhaps late Triassic time, Western North America was invaded from the north by the sea, and the

[1] W. T. Lee, "Reasons for Regarding the Morrison an Introductory Cretaceous Formation," *Bull. Geol. Soc. Amer.*, XXVI (1915), 303–14.

sediments of the Sundance formation were laid down; following this the sea retreated, the retreat taking place along with final Jurassic folding in the Sierra Nevada region. Over the plain exposed by the retreat of the Sundance sea the Morrison sediments were spread out in the form of a very broad, very flat alluvial fan from west to east. This fan must have been crossed by many large streams, dotted with lakes, large and small, and characterized by an interlacing type of drainage, much after the manner of the great alluvial plains of Eastern China at the present time. The plain must have been low, and the streams crossing it must have been characterized, for the most part, by a low gradient. Locally, especially in the western areas, there may, in fact must, have been some deposition in relatively swift currents, as indicated by the cross-bedded sandstones. These sandstones being rather fine-grained for the most part and never conglomeratic, true torrential conditions were probably not present in any part of the Morrison area so far studied. The round sand grains, associated with aeolian type of cross-bedding and sudden variations in thickness, indicate that wind deposition was also a factor in the gradual building up of the Morrison sediments. The presence of unaltered or little altered volcanic ash indicates that volcanic activity must have been going on somewhere in the region. Over a plain as broad and flat as this one must have been material could not have been transported rapidly from the original source to the outer limits of the area of sedimentation. The sluggish streams of the plain must have deposited material and later picked it up again and carried it farther very many times before a selected lot of sediment could have reached the outer margins. This will account for the greater relative abundance of finer clays in the eastern areas. The interlacing stream, lake, and swamp conditions on such a plain would readily admit of rapid shifting of the courses of streams, areas which were at one time stream beds constantly changing to interstream areas, and the reverse. This would result in the slow, gradual shifting of material outward. The end result would be the product of alternate deposition and erosion, erosion and deposition, for a long period of time, the material being very slowly worked eastward. In some such manner as this the relatively thin sheet of

Morrison sediments may have been spread out over a vast area. In this area of deposition, and living while it was in progress, were the Sauropoda and their contemporaries.

BIOTIC ENVIRONMENT

I. VERTEBRATES

The known vertebrate fauna of the Morrison is large and varied. The unknown fauna must have also been larger; perhaps, in fact quite likely, larger still. Of the mountain fauna of Morrison time nothing can be said, but the mountain fauna was not part of the sauropod habitat.

1. *Mammalia.*—Between twenty and thirty species of mammals have been reported from Morrison beds. These were small triconodonts, trituberculates, and multituberculates. They are known only from teeth and fragmentary jaws, so that their structure and adaptations cannot be made out. It has been suggested that they were arboreal. They might serve very well for arboreal members of the Morrison fauna. These small mammals could scarcely have competed with the Sauropoda for food; they certainly could not have constituted food for the Sauropoda in themselves; nor could they have been directly formidable as enemies. It has been suggested, however, that they may have fed, in part at least, upon reptilian eggs. If they did, and if they existed in large numbers, they may have been very troublesome companions for the sauropods.

2. *Aves.*—Only one species of bird is known from the Morrison. Undoubtedly more were present in Morrison time, but there is no direct evidence of their existence. It is not likely that the birds had any important effect upon the lives of the sauropods, although they may have had something to do with the distribution of species of plants which perhaps composed part of the sauropod diet.

3. *Reptilia.*—The reptilia of the Morrison were many and varied. They all represented degrees of organization and stages of evolution which were comparable to the degree of organization and stage of evolution of the member of the fauna under discussion—the Sauropoda. Undoubtedly there was competition of several sorts between the Sauropoda and their reptilian contemporaries.

The reptilian fauna of the Morrison suggests the following analysis:

a) Rhynchocephalia. The only modern representative of this group is non-marine, and there is nothing in the structure of the single Morrison representative of the order to suggest that it was anything different. It may perhaps have been amphibious, or fluviatile, or terrestrial. It is not probable that there was any direct competition between the members of this group and the sauropods.

b) Crocodilia. Several species of mesosuchian crocodiles are known to have existed in Morrison time along with the Sauropoda. The modern crocodiles are amphibious creatures, either fluviatile or lacustrine, not marine, and the Morrison forms probably lived in a similar manner. They were good-sized, active, carnivorous, relatively intelligent animals, which may easily have preyed upon the young of the Sauropoda.

c) Pterosauria. The pterodactyls were aërial forms. One species is known from the American Morrison. It is hardly to be expected that sauropod dinosaurs and pterosaurs would enter into any direct conflict or competition with each other.

d) Squamata. Lizards, snakes, and mosasaurs are entirely unknown from the Morrison. Some of them must have been living somewhere at the time, for lizards are known to have existed since the Triassic, and mosasaurs appear well developed early in the Cretaceous. Consider in this connection the fact that the mosasaurs were marine animals.

e) Chelonia. Turtles at the present time are marine, fluviatile, lacustrine, or terrestrial. Only one species in this group is known from the Morrison, and it is probable that the chelonian element in the Morrison fauna was not very important. The turtles could hardly have come into severe competition with the Sauropoda.

f) Sauropterygia and Ichthyopterygia. The plesiosaurs and ichthyosaurs were entirely marine. No trace of them has been found in Morrison rocks, though they must have been living in the sea during Morrison time. They are found in marine rocks both younger and older than the Morrison.

g) "Dinosauria." The two great orders of reptiles collectively known as "Dinosauria" were represented in the Morrison by a variety of forms. These were all terrestrial or amphibious, perhaps some forms being largely fluviatile or lacustrine. Of the saurischians there were present, besides the sauropods, several types of carnivorous forms. Some of these were small, active, and not very formidable. *Ornitholestes* may be considered as a typical example of this group. Probably these small dinosaurs had little importance, so far as the Sauropoda were concerned, unless, perhaps, they ate sauropod eggs. They were too small and weak to attack the sauropods, and by their activity and carnivorous structure could obtain food that would not be available for gigantic, largely herbivorous swamp dwellers. The larger carnivorous dinosaurs, such as *Allosaurus*, *Creosaurus*, and *Ceratosaurus* undoubtedly played a very important part in sauropod economy. The association of carnivore teeth and grooved sauropod bones is in perfect accordance with the idea that the sauropods were prey for the large carnivores. The large carnivores were unquestionably land-living forms. It is not at all likely that they entered the water except under unusual circumstances or along the margins. The gigantic sauropods, therefore, were less likely to be attacked in the water than on land. This may have tended to keep the sauropods in the water, and may have had considerable control over the evolution of the group. The ornithischian dinosaurs must also have had an effect upon the Sauropoda, but as competitors rather than as direct enemies. The stegosaurs and the iguanodonts, both large and small, existed along with the sauropods. These forms, especially the stegosaurs, were probably land animals. They were herbivorous beyond all doubt. If the sauropods spent a considerable part of their time on land they must have come into competition with the predentates in the matter of getting food. Perhaps such a competition took place early in the history of the Sauropoda, and may have been instrumental in forcing the latter to take to the streams, and finally to develop some aquatic adaptations and spend the greater part of their time in the water. The predentates may have aided the sauropods in their struggle for existence by furnishing a considerable amount of food for the carnivores. If the predentates

and carnivores were almost exclusively terrestrial and the sauropods largely aquatic in habit, the latter might escape the carnivores much more frequently than if the predentates were not present.

4. *Amphibia.*—The known amphibian fauna of the Morrison consists of one frog or toad. A fauna of this nature could scarcely have had any effect upon the lives or development of the Sauropoda.

5. *Pisces.*—The only fishes known to have existed along with the American Sauropoda were a few species of *Ceratodus*. These could hardly have furnished food for the sauropods, or have had any direct effect upon the security of the latter.

II. INVERTEBRATES

The known invertebrate fauna of the Morrison is neither very large nor varied. It consists of a number of fresh-water pelecypods and gastropods, together with a few ostracods. None of these were large enough nor abundant enough to have served as an essential part of the diet of the sauropods, but they may have served as accessories, to a very small extent, to the normal sauropod diet.

III. FLORA

The known flora consisted almost entirely of cycads. These might also have comprised an accessory portion of the sauropod diet, but probably not much more. The remainder of the Morrison flora is very little known. Silicified wood is found occasionally, and rarely some imperfect reeds. The Kootenie formation contains leaves of deciduous trees, but few if any sauropods. The Arundel formation of Maryland contains both sauropod bones and deciduous leaves. The latter also might have formed an accessory part of the food of the sauropods, but could scarcely have been abundant enough to have sustained their huge bulk. In a region such as the one described above there might have been a considerable amount of soft vegetation which would not be easily preserved. In the interstream areas, especially where considerable amounts of windblown sands were being deposited, little vegetation may have been present, certain areas being semiarid. Other areas were probably well covered with vegetation. The character of the known flora suggests a rather warm climate, and the physical

conditions point more to an abundance of rainfall than to a widespread lack of it. We may therefore conclude, provisionally at least, that the climate was warm and moist.

INTERPRETATION OF HABITAT

From the evidence of the physical characters of the Morrison formation and from the nature of its flora and fauna it may be possible to work out, to a certain degree at least, the environment which surrounded our American Sauropoda. In the first place, there was a vast plain in the Western United States, possibly extending northward into Canada; this plain was low throughout its entire extent, but slightly higher in the west than in the east; it was bordered on the west by mountainous country. From this mountainous area streams issued, bringing sediment and depositing it along the western border of the plain. The streams, upon leaving the mountains, became sluggish and split up into a large number of distributaries. As in the great plains of China, streams would be split up into distributaries and united again. Between the streams, and more or less connected with them, were lakes. A considerable amount of vegetation was present, especially along the stream and lake banks. In this respect the plain would resemble the interior of Florida, which has often been suggested as the type of habitat possible for sauropod dinosaurs. Our Morrison plain would differ from Florida, however, in its extent, the central Florida swamps being relatively small and the Morrison plain being a million square miles or more in area. In some of the interstream areas, especially in the west, vegetation may have been more scarce. Active volcanoes were present somewhere, either in the mountains or on the plain. Somewhere to the southeast was the sea, but its exact border is not known, especially with regard to the earlier part of Morrison time. On this plain lived an extensive terrestrial, amphibious, fluviatile, or lacustrine fauna. Little, primitive mammals climbed the trees or scurried over the ground; here and there some birds flew through the air; along the shores of the lakes and rivers lived some Sphenodon-like rhynchocephalians; pterosaurs flew through the air; some turtles swam about in the water; crocodiles inhabited the stream and lake banks, and infested the

waters themselves. On land, large and small carnivorous dinosaurs roamed about, seeking what they might devour; stegosaurs and camptosaurs endeavored to escape their voracious contemporaries; some frogs inhabited the swamps. In the rivers and lakes lung fish swam about. Fresh-water mollusks and crustaceans lined the river and lake bottoms in places or swam about freely in the water. Cycads grew in abundance, and soft swamp vegetation probably furnished the food supply for hungry reptiles. In some such environment as this, or at any rate in one very much like it, lived the American sauropod dinosaurs. So far as is indicated by evidence now directly available, conditions of practically the same sort prevailed in other parts of the world inhabited by Sauropoda.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Washington, Henry S. "Some Lavas of Monte Arci, Sardinia," *Amer. Jour. Sci.*, XXXVI (1913), 577–90, analyses.

The extinct volcano Monte Arci has not been described since 1857. It consists of a core of rhyolite with later dacites, andesites, trachytes, and basalts. The various lavas are described petrographically and chemically. Seven analyses are given and they are recomputed in the C.I.P.W. system.

Washington, Henry S. "The Composition of Rockallite," *Quart. Jour. Geol. Soc.*, LXX (1914), 294–302.

This paper describes a peculiar aegirite-granite from Rockall. A chemical analysis gives SiO_2 69.80, while a previous and probably accurate analysis of the other half of the same specimen gave 73.60. This shows the great variation possible in a single small specimen.

Washington, Henry S. "An Occurrence of Pyroxenite and Hornblendite in Bahia, Brazil," *Amer. Jour. Sci.*, XXXVIII (1914), 79–90, analyses.

Describes a hornblendite with a border of pyroxenite intruded in gneiss. The rocks contain considerable manganese. They are interesting since they possess absolutely no feldspar and yet show from 18 to 30 per cent in the norms.

Washington, Henry S. "I Basalti Analcitici della Sardegna," *Boll. Soc. Geol. Ital.*, XXXIII (1914), 147–67.

A translation of "The analcite basalts of Sardinia" which appeared in this Journal, Vol. XXII (1914), 742–53.

WASHINGTON, HENRY S. "Contributions to Sardinian Petrography. I. The Rocks of Monte Ferru," *Amer. Jour. Sci.*, XXXIX (1915), 513–29, figs. 2, analyses.

In this paper are described trachyte, trachytic phonolite, basalt, and analcite-basalt from Monte Ferru, Sardinia.

WASHINGTON, HENRY S. "The Calculation of Calcium Orthosilicate in the Norm of Igneous Rocks," *Jour. Wash. Acad. Sci.*, V (1915), 345–50.

Calcium silicate, which was originally calculated in the C.I.P.W. system as $4CaO.3SiO_2$, was later (1912) revised as $3CaO.2SiO_2$. This is again revised and now the orthosilicate $2CaO.SiO_2$ is used in calculating the norm. A table is given which may be cut out and pasted over the akermanite table given in the C.I.P.W. book.

WASHINGTON, HENRY S. "The Correlation of Potassium and Magnesium, Sodium and Iron in Igneous Rocks," *Proc. Nat. Acad. Sci.*, I (1915), 574–78.

The writer shows that in igneous magmas potassium and magnesium on the one hand and sodium and iron on the other probably vary together.

WASHINGTON, H. S., and DAY, ARTHUR L. "Present Condition of the Volcanoes of Southern Italy," *Bull. Geol. Soc. Amer.*, XXVI (1915), 375–88, pls. 9.

A record of the state of activity and other conditions at Vesuvius, Ætna, and the Æolian Islands during the summer of 1914. The general results of the observations and studies of gases, salts, and rocks collected will be given in a subsequent paper.

WATSON, THOMAS L., and TABER, STEPHEN. "Magmatic Names Proposed in the Quantitative System of Classification for Some New Rock Types in Virginia," *Bull. Phil. Soc. Univ. of Virginia Scientif. Ser.*, I (1913), 331–33.

Proposes four new names in the C.I.P.W. system, for rocks found in Virginia.

WATSON, THOMAS L., and CLINE, JUSTUS H. "Petrology of a Series of Igneous Dikes in Central Western Virginia," *Bull. Geol. Soc. Amer.*, XXIV (1913), 301–34, pls. 3, figs. 5, analyses.

Describes a series of dikes occurring in Rockbridge, Augusta, Rockingham, and Highland counties, Virginia. The rocks are diabase, granite-felsophyre, quartz-gabbro, nephelite-syenite, teschenite, and camptonite. All the rocks are analyzed and their positions in the C.I.P.W. system are determined.

WATSON, THOMAS L., and TABER, STEPHEN. "Geology of the Titanium and Apatite Deposits of Virginia." *Bull. III–A, Virginia Geol. Surv.*, 1913. Pp. 308, pls. 37, figs. 22, 7 pp. bibliography on titanium.

After a general discussion of the titanium minerals and a brief description (28 pp.) of the rutile deposits of the world, the geology of the ore deposits in the Amherst-Nelson region is given. The rocks are described in detail, and chemical analyses of some of the associated rocks—biotite-quartz-monzonite-gneiss, syenite, gabbro, nelsonite, and diabase—are given. In the first the plagioclase is oligoclase, Ab_2An_1; the second rock is really an andesinite, or andesine-anorthosite as used by the authors; the rock described as gabbro consists chiefly of andesine and hypersthene with ilmenite, apatite, orthoclase, quartz, biotite, etc.; the nelsonite is a dike-rock consisting essentially of ilmenite and apatite.

WHERRY, EDGAR T. "A Peculiar Oolite from Bethlehem, Pennsylvania, *Proc. U.S. National Mus.*, XLIX (1915), 153–56, pls. 2.

Describes an oolite in which the ooids show a "half-moon" effect, the upper portions being light and the lower dark. An explanation for this peculiar character is given.

WHERRY, EDGAR T., and GORDON, SAMUEL G. "An Arrangement of Minerals According to Their Occurrence," *Proc. Acad. Nat. Sci., Philadelphia*, 1915, 426–57.

Minerals are classified according to their occurrence in igneous rocks, pegmatites, hydrothermal deposits, fumerolic deposits, or sediments. Each of these main divisions is subdivided into various groups, and under each is given a list of the minerals which occur. It is a very useful list.

WHERRY, EDGAR T. "The Microspectroscope in Mineralogy." *Smithsonian Miss. Col.*, LXV (1915), No. 5. Pp. 16.

Descriptions of the spectra observed in the examination of about 200 minerals with the microspectroscope.

WILKMAN, W. W. "Kaleviska bottenbildningar vid Mölönjärvi." *Bull. com. géol. Finlande*, No. 43, 1915. Pp. 36, figs. 11.

A geological description of the basal formations near Lake Mölönjärvi, in east Finland. Granite, conglomerate, quartzites, various schists and phyllites, and basic dikes are described.

WRIGHT, FRED. EUGENE. "An Electrical Goniometer Furnace for the Measurement of Crystal Angles and of Refractive Indices at High Temperatures." *Jour. Wash. Acad. Sci.*, III (1913), 396–401.

Describes a furnace for measuring the interfacial angles and refractive indices of crystals at temperatures up to 1225°.

WRIGHT, FRED. EUGENE. "Graphical Methods in Microscopical Petrography," *Amer. Jour. Sci.*, XXXVI (1913), 509–39, pls. 8, figs. 9.

The writer gives eight charts for the solution of the following equations: $\sin i = n \sin r$, $\sin^2 i = n^2 \sin^2 r$, $\cot A = B . \cot C$, $\sin A = \sin B . \sin C$,

$$\frac{\gamma^1 - \alpha^1}{\gamma - \alpha} = \sin \theta_1 \sin \theta_2, \quad \tan^2 V\alpha = \frac{\frac{1}{\beta^2} - \frac{1}{\gamma^2}}{\frac{1}{\alpha^2} - \frac{1}{\beta^2}}, \quad \tan V\alpha = \sqrt{\frac{\frac{1}{\beta^2} - \frac{1}{\gamma^2}}{\frac{1}{\alpha^2} - \frac{1}{\beta^2}}}.$$

WRIGHT, FRED. EUGENE. "The Change in the Crystal Angles of Quartz with Rise in Temperature," *Jour. Wash. Acad. Sci.*, III (1913), 485–94, figs. 2.

The polar angle ρ of the unit rhombohedron was found to decrease at an increasing rate until the temperature of 575° was reached. Here, with the inversion of α-quartz to β-quartz there is an abrupt decrease of 2′ in the angle, and the value remains constant thereafter to 1250°.

WRIGHT, FRED. EUGENE. "The Measurement of the Refractive Index of a Drop of Liquid," *Jour. Wash. Acad. Sci.*, IV (1914), 269–79, figs. 14.

Describes various methods for measuring the refractive index of liquids, five of them new methods for the petrographic microscope.

WRIGHT, FRED. EUGENE. "The Determination of the Relative Refringence of Mineral Grains under the Petrographic Microscope," *Jour. Wash. Acad. Sci.*, IV (1914), 389–92.

Describes a new diaphragm for observing relative refractive indices.

WRIGHT, FRED. EUGENE. "The Optical Character of the Faint Interference Figure Observed in High Power Objectives between Crossed Nicols," *Jour. Wash. Acad. Sci.*, IV (1914), 301–09.

Explains the positive character of the interference figure produced by the rotation of the vibration plane of the transmitted light.

WRIGHT, FRED. EUGENE. "A New Half-Shade Apparatus with Variable Sensibility," *Wash. Acad. Sci.*, IV (1914), 309–13.

Describes a device for varying the sensibility of a half-shade apparatus.

WRIGHT, FRED. EUGENE. "A Simple Method for the Accurate Measurement of Relative Strain in Glass," *Jour. Wash. Acad. Sci.*, IV (1914), 594–98.

Describes a wedge with which it is possible to measure path-differences of less than $1\mu\mu$.

WRIGHT, FRED. EUGENE. "Measurements of Refractive Indices on the Principal Optical Sections of Birefracting Minerals in Convergent Polarized Light," *Jour. Wash. Acad. Sci.*, IV (1914), 534–42.

Two refractive indices are measured by the immersion method, the third by measurements made on the rings in the interference figure.

WRIGHT, FRED. EUGENE. "The Accurate Measurement of the Refractive Indices of Minute Crystal Grains under the Petrographic Microscope," *Jour. Wash. Acad. Sci.*, V (1915), 101–7.

Considers the conditions necessary for the exact measurement of refractive indices of minute crystal particles by the immersion method.

WRIGHT, FRED. EUGENE. "A New Crystal-Grinding Goniometer," *Jour. Wash. Acad. Sci.*, V (1915), 35–41.

Describes the precision goniometer used in the Geophysical Laboratory, which is capable of grinding a plate to within 1′ of the required position.

WRIGHT, FRED. EUGENE. "Obsidian from Hrafntinnuhrygghur, Iceland. Its lithophysae and Surface Markings," *Bull. Geol. Soc. Amer.*, XXVI (1915), 255–86, figs. 12.

The writer discusses the formation of spherulitic, lithophysal, and pumiceous structures in the obsidians of Iceland, as well as certain markings produced by the etching effect of hot volcanic gases.

WRIGHT, FRED. EUGENE. "The Position of the Vibration Plane of the Polarizer in the Petrographic Microscope," *Jour. Wash. Acad. Sci.*, V (1915), 641–44.

The writer concludes that there is a slight practical advantage in having the plane of vibration parallel to the vertical cross-hair.

WRIGHT, FRED. EUGENE. "A Simple Device for the Graphical Solution of the Equation $A=B.C$," *Jour. Wash. Acad. Sci.*, VI (1916), 1–5.

Describes a device by means of which certain formulae may be solved by the use of a series of scales.

WRIGHT, FRED. EUGENE. "A Geological Protractor," *Jour. Wash. Acad. Sci.*, VI (1916), 5–7.

A device for solving various problems, such as the slope of any bed, in the field.

WÜLFING, E. A., and BECHT, K. "Über neue Turmalinanalysen," *Sitzb. Akad. Wiss. Heidelberg*, 1913. A–20. Pp. 10, analyses.

WÜLFING, E. A. "Über Kristallwinkel bei verschiedenen Temperaturen," *Sitzb. Akad. Wiss. Heidelberg*, 1913. A–21. Pp. 5, figs. 2.

In the determination of the changes produced in crystal angles it is sometimes necessary, on account of the irregular natural faces, to grind artificial faces. The present paper deals with the question as to the most advantageous angle at which they should be cut, and the conclusion is reached that this is 45° with the base. If possible it is better to measure across the base from one pyramidal face to another, thus (101) to ($\bar{1}$01).

WÜLFING, E. A., and OPPENHEIMER, L. "Neue Untersuchungen an Cordierit," *Sitzb. Akad. Wiss. Heidelberg*, 1914, A–10. Pp. 13, figs. 1.

New determinations on cordierite from eight localities.

WÜLFING, E. A., and HÖRNER, F. "Die kristallographischen Konstanten des Stauroliths vom St. Gotthard," *Sitzb. Akad. Wiss. Heidelberg*, 1915, A–10. Pp. 11.

Gives new determinations of interfacial angles and axial ratios.

WÜLFING, E. A. "Lassen sich die kristallographischen Fundamentalwinkel der Plagioklase mit der Zusammensetzung in gesetzmässige Beziehung bringen?" *Sitzb. Akad. Wiss. Heidelberg*, 1915, A–13. Pp. 24, figs. 6.

New determinations of crystallographic properties make it possible to say with certainty that these properties follow a definite law.

ZIEGLER, VICTOR. "The Minerals of the Black Hills." *Bull. 10, South Dakota School Mines*, 1914. Pp. 255, map 1, pls. 30, figs. 26, bibliography.

In this bulletin the writer describes briefly, for the benefit of the miner, prospector, and student, all the minerals known to occur in the Black Hills. There are included three very good tables for the megascopic determination of the minerals, as well as many full-page illustrations.

The book should be of great value to everyone working in the Black Hills region.

Reviews

Geology and Paleontology of the Raton Mesa and Other Regions in Colorado and New Mexico. By Willis T. Lee and F. H. Knowlton. U.S. Geological Survey, Professional Paper No. 101, 1917. Pp. 450, pls. 103, figs. 16.

This interesting paper presents many details concerning the geology of the areas indicated by the title. To the general reader the large interest of the paper centers in the correlation of disputed formations in the several regions discussed, and in the attempt to establish their time-relations to formations elsewhere. Some of the significant conclusions are the following:

"The coal-bearing rocks of the Raton Mesa region which have formerly been referred to the Laramie constitute two distinct formations separated in time by a period of erosion." The lower of these two formations (Vermejo) contains a Montana flora, and "is more closely related to the Mesa Verde of western New Mexico than to any other formation we have examined." The coal-bearing rocks of the Canyon City field are correlated with the Vermejo, which is thought to be approximately equivalent in age to the Fox Hills formation of the Denver basin.

"The upper coal-bearing formation of the Raton Mesa region, to which the name Raton is here applied, is Eocene in age and contains a flora distinct from that of the Laramie of the Denver basin, but similar to that of the post-Laramie formations of that basin and to that of the Eocene Wilcox group of the Gulf coast."

"The unconformity between the Vermejo and Raton formations represents a time interval comparable to that . . . . separating the Laramie from the Arapahoe of the Denver basin."

"The coal-bearing rocks of the Cerrillos, Hagan, Tijeras, and Rio Puerco fields are essentially equivalent in age to the Mesa Verde of the San Juan basin."

The plants of the formations described in this paper are discussed by Mr. F. H. Knowlton, who indicates that the flora of the Raton formation indicate "a relatively moist, warm situation, whose temperature did not fall much if any below 42°F," and that the floral hiatus between the

Vermejon and Raton floras can be explained only by the lapse of a very long period of time. Specifically Mr. Knowlton, on the basis of plant fossils, correlates the Raton formation with the Wilcox formation, and "probably with the Midway formation of the Gulf region."

The paper tends to confirm the conclusion which has been growing for many years that the Raton and equivalent formations are of Eocene—not of Cretaceous—age.

The general conclusion is reached that the Raton formation is essentially equivalent to the Arapahoe, the Denver, the Dawson, the Fort Union, the Wilcox, and perhaps the Midway formations.

R. D. S.

My Reminiscences. By RAPHAEL PUMPELLY. New York: Henry Holt & Company, 1918. 2 vols. Pp. 844, maps, ills.

In these two volumes the reader will find a most fascinating story of the very remarkable adventures and varied experiences which were crowded into the long life of this eminent American geologist. As the central figure was an inveterate traveler, roaming over a large portion of the globe when traveling was vastly different from what it now is, the work is first and foremost a book of travel.

After studying at Freiberg and taking long vacation rambles through the mountains of Corsica and various other parts of Europe as the fancy struck him, Pumpelly returned to the United States and in 1860 began his professional work at the Santa Rita mines in Arizona. The Apache terror was then at its height, and Pumpelly alone of five successive superintendents of the mine was not murdered. Chance then took him to Japan, where in the employ of the Japanese government he conducted geological investigations and introduced certain improvements into Japanese methods of mining. It was but one step more to China, where a year and a half were devoted to private travels and geological exploration for the imperial government—experiences and researches which are vividly sketched. For the return journey to America several alternative routes were open, but with the true instinct of adventurous travel the author chose a winter journey across Mongolia and Siberia to Europe by saddle-horse and sleigh.

In our own country the author's most significant explorations were those in the Lake Superior region between 1867 and 1871, when the Lake Superior iron ores were beginning to attract attention. These reminiscences are of special interest for the light they throw on the discovery and beginnings of the Menominee and Gogebic iron ranges. It was here in

1871 that Pumpelly, owing to a combination of circumstances, declined the chance to take up all the even-numbered sections along twenty miles of the Gogebic iron range and thus, as he himself expressed it, "missed the opportunity of a lifetime."

In 1903–4 occurred what the author regards as the most interesting part of his life—namely, the Carnegie expedition to Turkestan under his leadership. The purpose was to test the hypothesis that Central Asia was the primitive home of the Aryan race, by studying the traces of prehistoric civilizations and seeking evidences of geological and climatic changes during and since the glacial period. In a way it was the climax of the author's travels and professional work. Excavation at Anau in southern Turkestan revealed, among other things, the fact that the Stone Age inhabitants of this region used stone sickles with sharp cutting edges, while arrowheads and weapons of the chase were unknown to them. From this and other lines of evidence it seemed safe to conclude that the Neolithic peoples of Turkestan were not hunters but agriculturalists.

Though sketching a scientific career, the topics treated are so spiced and stocked with amusing anecdotes that they must appeal strongly to the general reader as well as to the geologist. The narrative is lively and always interesting.

R. T. C.

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TWO-PHASE CONVECTION IN IGNEOUS MAGMAS[1]

FRANK F. GROUT
University of Minnesota

A careful study of the Duluth gabbro led the writer to the idea of a convection circulation in the magma. A review of the literature shows nothing conclusively opposed to the idea, though the structures are explained in many other ways. This paper summarizes the signs of convection and suggests its probable mechanism and results.

SIGNS OF CONVECTION IN MAGMAS

1. The fluxion structure of many rocks is a strong indication that movement occurred during crystallization. When combined with an alternation of differentiated bands and a roughly gravitative arrangement of the bands, the only explanation that is at all satisfactory is that the movement is one of circulation rather than of intrusion or of deformation.[2]

2. Convection has been observed directly in lava lakes in the craters of volcanoes. These highly special conditions of magma, however, are not sufficient to convince everyone that convection is a common process in deeper magmas.

[1] Part of a thesis presented to the faculty of Yale University for the degree of Doctor of Philosophy.

[2] Frank F. Grout, "Internal Structures of Igneous Rocks," etc., *Jour. Geol.*, XXVI, No. 5 (1918).

3. The texture of an intrusive mass in relation to its borders and its contact metamorphism may be a sign of convection. Lane[1] and Queneau[2] have shown that in the case of simple conduction of heat away from a stationary mass the grain of the rock will not be uniform up to the contact unless the magma temperature was farther above the temperature of crystallization than the wall-rock temperature was below. As Lane puts it, measured from the temperature of the surrounding rock as zero, the magma must be more than twice the temperature of solidification. For an intrusion at moderate depths into cold rocks, this means more superheat than is commonly supposed to exist. The observed superheat is seldom over 200° to 300° C.

4. The arrangement of the extreme differentiates in a laccolith might be a strong indication of convection. If the outer layer is of average composition it may be attributed to chilling, but if a layer found on all sides, top and bottom, is an extreme of the series of differentiates it can be attributed to neither chilling nor gravity. An illustration is found in the Lugar sill in Scotland.[3] The average material of the sill has scarcely 20 per cent of salic constituents, but the border phases have over 40 per cent of feldspar and feldspathoid material. Since diffusion is shown to be too slow a process,[4] the only way to get the extreme product segregated to all sides is by a circulation of some sort.

5. A differentiated dike found by the writer at Duluth is very suggestive. The dike is four feet wide and is pegmatitic in nature a few feet below the base of the main gabbro. Its texture is particularly coarse at the sides, where the composition is that of a gabbro, and it is evident that the crystals must have grown large by additions from the residual circulating or passing magma in the center of the dike. From these coarse gabbro borders there is a complete gradation to a medium-grained red granite in the center of the dike.

[1] A. C. Lane, "The Grain of Rocks," *Bull. Geol. Soc. Am.*, VIII, 403.

[2] A. L. Queneau, *School of Mines Quarterly*, XXIII (1902), 181.

[3] G. W. Tyrrell, "Alkaline Igneous Rocks of West Scotland," *Geol. Mag.*, IX (1912), 75–77.

[4] N. L. Bowen, "Later Stages of Evolution of Igneous Rocks," *Jour. Geol.*, Supplement, December, 1915, p. 12.

There is no sign whatever of an internal contact between the two rocks such as would indicate successive intrusions. Neither is there any fluxion structure such as a strong extrusive movement during crystallization would be expected to produce. It is much more likely that the gabbro and granite separated from the same liquid, and that this was moved about only slightly, by convection or by a late phase of injection, so that the supply of basic minerals to the sides was continuous until all had crystallized.

THE MECHANICS OF CONVECTION IN IGNEOUS MAGMAS

The nature of convection.—The familiar illustration of convection is the local heating of a tank of water, with some suspended matter to make its motion visible. The density in different parts of the tank is different enough to start a motion of readjustment, and if the difference is maintained by a continuous heat supply and continuous cooling elsewhere, a circulation is maintained. As applied to magmas the process was suggested by Becker and has been widely applied.[1] The chief factors which control the rate of circulation are the differences in density in different parts of the container and the viscosity of the liquid; and both of these factors vary with temperature. Water, which is the liquid in most laboratory experiments, shows a very great density change with temperature, and its viscosity is very low as compared with that of igneous magma. Both conditions being exceptionally favorable, it is clear that the illustration should not be applied to magmas without some estimate of its quantitative importance.

Two-phase convection.—Besides the well-known changes in density in a magma from changes of temperature, there are other density effects due to a separation of phases. The separation of gases and crystals from lava is a matter of common observation. The separation of gases was suggested by Pirsson[2] as a possible means of deep-seated stirring, and the idea was further developed by

[1] G. F. Becker, "Some Queries on Rock Differentiation," *Am. Jour. Science*, III (1897), 21. L. V. Pirsson, "The Igneous Rocks of the Highwood Mountains," *U.S. Geol. Surv. Bull. 237*, pp. 184 and 189.

[2] L. V. Pirsson, "The Petrographic Province of Central Montana," *Am. Jour. Sci.*, XX (1905), 47.

Daly[1] in explaining the supply of heat from depth to lava lakes—he called it two-phase convection.

It seems perfectly clear, from a general consideration of the idea, that a mass of lava filled with bubbles would have a lower "aggregate specific gravity" than a neighboring mass without such bubbles. Any process of local vesiculation would almost certainly result in convection. It is perhaps less clear and less often emphasized, but none the less true, that a mass of lava in which crystals have formed has a greater "aggregate specific gravity" than it had just before, and a local development of crystals would also almost certainly start convection. In the case of gas bubbles in a magma the escape of the gas from a crater lake would finally remove the cause of the circulation. In order to maintain the circulation there must be a continuous supply of gas bubbles to some portion of the magma. Similarly, if crystals settle out of a liquid magma they would no longer tend to move the liquid. The circulation caused by the density of crystals would be active only during the time in which crystals were developing locally in the liquid and settling through it. However, in a large body of magma either of these processes might be maintained for a long time.

THE DEVELOPMENT OF PHASES IN MAGMAS

Phases are defined in physical chemistry as the parts of a system which are mechanically separable. A simple magma consists of one liquid phase. Considered as a solution, the magma may contain various dissolved substances, including many minerals as well as gases and water; but it remains one phase and only one.

Gas phase.—When bubbles of gas separate from solution in a magma and remain in it as parts of a closed system (i.e., do not mingle with the outside air), they may be considered a second phase in the magma. The conditions and reasons for their separation are various. The solubility of gas in a liquid varies with the pressure. If a magma saturated with gas at a pressure of 200 atmospheres is erupted to the surface, where the pressure is one atmosphere, gas will separate from the solution. It is equally sure

[1] R. A. Daly, "The Nature of Volcanic Action," *Proc. Am. Acad. of Arts and Sci.*, XLVII, 76.

to separate if intruded in a region of less pressure, even if it does not reach the surface. The solubility of a gas also varies with the temperature and with certain changes in the composition of the magma. For example, the assimilation of other rocks or liquids may so change the composition as to make the gas less soluble. It becomes evident that gases may separate at considerable depth as well as at the surface.

Crystal phase.—It is a commonplace that a magma on cooling and under various modifying influences will crystallize in a series of mineral compounds. In the closed system, with some of the mother-liquor, each constitutes a phase.

New liquid phases.—The question of immiscibility in magmas may be left open. While it is not well to use the term as if the process were known, the discussion of probable cases would not be complete without the consideration of new liquid phases. Changes in temperature or composition are the explanations given for their separation.

FACTORS IN MAGMA MOVEMENTS

The points to consider in a discussion of convection are the forces applied and the viscosity and related effects tending to oppose or retard movement. We are not now concerned with the forces leading to the intrusion of magmas. The estimate of forces is wholly dependent on specific gravities and on the volume of the portions of different specific gravities. These must be estimated. The viscosity of magmas is known to be variable with composition, pressure, and temperature; and in the present case we must estimate the added effect of the presence of a second phase.

Viscosity.—The factor of viscosity is so great that by many the possibility of active convection in a crystallizing magma is dismissed as an absurdity; but the field evidence is strong enough to warrant a quantitative estimate. Furthermore there may be in the minds of many a misconception of the true nature of increased viscosity. A truly viscous fluid, as distinct from a weak solid, will yield to any small force if given time. Viscosity cannot inhibit the movement, but can only retard it. In a pitch a million of million times as viscous as water, stones will sink and cork will rise in a few weeks.

On the other hand, in as weak a solid as gelatine gas bubbles and small solids remain stationary indefinitely. Bowen's work on the settling of crystals[1] may be taken as evidence that a magma during crystallization is truly viscous. In such a liquid, then, any appreciable force applied is entirely sufficient to start action. It simply remains to estimate possible counteracting forces and the rate of motion likely to result.

It was estimated by Becker[2] that Hawaiian lavas were about fifty times as viscous as water (0.575 in C.G.S. units; water at 15°, 0.0115). Daly[3] estimates that rhyolites may be erupted at a viscosity of 11.5. Ranging from these values for actively moving magmas, we may be sure that on cooling the viscosity increases until in glasses it is almost infinite. Data connecting the viscosity with temperature are not available. Fortunately Bowen has noted the rate of settling of certain crystals and thus obtained some very useful estimates for viscosity *during crystallization*,[4] which is the condition of most importance rather than the actual temperature. His figures for probable maximum viscosities are 4 to 200 in C.G.S. units for melts ranging from basic to acid character, in which crystals are growing. Bowen calls these figures maxima because of the probable growth of the crystals during settling. Several factors tend to reduce the values in nature. The extreme fluidity actually shown[5] by intrusive magmas may be due to their retention of more water vapor than is the case in extrusive lavas. In agreement with this are the results of Morey[6] showing that fusions in the presence of steam show a remarkable decrease in viscosity. The importance of water in magmas is attested by hydrous minerals and miarolitic cavities in the rocks. On the other hand, some conditions may increase viscosity. Doelter found that pressure increased it, but

[1] N. L. Bowen, "Crystallization Differentiation in Silicate Melts," *Am. Jour. Sci.*, XXXIX (1915), 186.

[2] G. F. Becker, *op. cit.*, p. 29.

[3] R. A. Daly, "Mechanics of Igneous Intrusion," *Amer. Jour. Sci.*, XXVI (1908), 30.

[4] N. L. Bowen, "Crystallization Differentiation in Silicate Melts," *Am. Jour. Sci.*, XXXIX (1915), 186.

[5] A. Harker, *The Natural History of Igneous Rocks*, p. 223.

[6] G. W. Morey, "New Crystalline Silicates of Sodium and Potassium," *Jour. Amer. Chem. Soc.*, XXXVI (1914), 226.

added that 10,000 meters of rock would probably increase it no more than 30 per cent.[1] This estimate, like the others, may be modified 100 per cent or more by careful work, but may be taken as of the approximate order of magnitude. Applying this addition to Bowen's figures, we have as probable maximum viscosities in even figures 5 to 300 in C.G.S. units.

The effect of new phases remains to be considered. It may be assumed that moderate amounts of a gas or liquid phase will have little effect on the motion of bodies of magma. The accumulation of crystal phases, however, may give a decided difference in results. Direct data not being available, it is well to consider analogous cases. Curves have been drawn showing the effect of clay added to water and dilute water solutions. Though the increase in viscosity may be great in some cases, it is shown that a slip with 50 per cent solids may have a viscosity less than 10 per cent greater than that of water.[2] A rough test by the writer, with starch and rock powders of about 80 mesh, up to 25 per cent of volume, showed an increased bulk viscosity of less than 5 per cent. This would have little effect on the maxima above estimated. Bowen estimates that a magma may be eruptible even with 50 per cent crystals.[3] The maximum viscosities assumed in this paper will therefore be from 5 to 300.

The thermal gradient in magmas.—The variations in temperature in different parts of a magma during the cooling process have not often been estimated. Estimates of the thermal gradient in a magma occupying a chamber may be made from the calculations and assumptions of several authors, but they vary from 100° to 300° C.[4] Since it is here argued that convection would occur, let us assume that cooling occurs without convection, and calculate the forces tending to start such convection. For example, assume

[1] C. Doelter, *Physikalisch-chemische Mineralogie* (1905), p. 110.

[2] A. V. Bleininger, *U. S. Bureau of Standards Technologic Paper 51* (1915), pp. 25–30.

[3] N. L. Bowen, "Later Stages of Evolution of Igneous Rocks," *Jour. Geol.*, Supplement, December, 1915, p. 31.

[4] R. A. Daly, *Igneous Rocks and Their Origin*, pp. 224 and 258; A. Harker, *op. cit.*, p. 316; A. C. Lane, "Coarseness of Igneous Rocks," *Amer. Geol.*, XXXV (1905), 71; Ingersoll and Zobell, *Mathematical Theory of Heat Conduction*, etc. Ginn & Co., 1913.

that a magma at 1,300°C. may be intruded at a horizon a mile below the surface which may have a temperature not over 100°, average probably 50°. The heat loss can be calculated by the formula

$$Q=\frac{kAt(T-T_1)}{x},$$

where k is the conductivity in C.G.S. units, A the area in square centimeters, and $(T-T_1)$ the difference in temperature. So long as the surface of the earth was kept cool, the upward flow of heat would be fairly uniform until the magma cooled appreciably. On the other hand, the temperature at the floor will not remain uniform. The floor of the Duluth gabbro must have sunk nearly 10 miles. The isogeotherms would rapidly rise. The lava streams that fed the intrusion and even the approach of the magma chamber below would contribute to the rapidity of the rise. With these supplies of heat from below, the heat added to the floor by the gabbro would accumulate rather than pass on. A rough calculation by the same formula indicates that the gabbro added heat to its floor in a year equivalent to a general rise in temperature of 12° for the first mile. In 100 years the floor would be so hot that heat losses in that direction would be very small. The gabbro as a whole, however, would cool only a few degrees in 100 years. Thus it seems that by the time crystallization begins the loss of heat is likely to be from the top and sides of the chamber. If this loss occurred without convection—say from a zone 10 to 15 meters thick at the roof—this zone would be cooled 100° below the main body of the magma very soon, say within a month. In a few years the contrast in temperature would be much greater. It is therefore assumed that a difference in temperature of 100°C. in different parts of a medium to large magma is not unusual.

The specific gravities of phases.—Specific gravity varies with composition, temperature, and crystalline or glassy structure. Daly, in summarizing the results of several investigators, estimates that the change from liquid to crystalline rocks at the same temperature results in an increase of specific gravity as follows: 6 per cent for gabbros and diorites, 7 per cent for quartz-diorite, 8 per cent

for syenite, and 9 per cent for granite.[1] The data need confirmation, as authorities disagreed as much as 100 per cent. The difficulty of accurate estimates has been shown by Day, *et al.*[2] The expansion with temperature is estimated at 0.000025 volume per degree Centigrade, but is greater for liquids than solids.[3] From these one may roughly estimate the proper order of magnitude as given in Table I, though the figures may be far from accurate in detail. Attention is called to the small differences due to temperature alone as compared with larger ones due to a change from liquid to solid and to changes of composition.

TABLE I

APPROXIMATE SPECIFIC GRAVITIES OF PHASES IN MAGMAS

	At 1000°		At 1100°	
	Solid	Liquid	Solid	Liquid
Average Granite	2.63	2.40	2.62+	2.39
Quartz	2.60	2.37	2.59	2.36
Orthoclase	2.49−	2.27	2.48	2.26
Average Gabbro	2.92	2.75	2.91+	2.74
Plagioclase, Ab_6An_1	2.58	2.41	2.57	2.40
Plagioclase, Ab_1An_1	2.62−	2.46	2.61	2.45
Magnetite	5.05	4.80	5.03	4.77
Olivine	3.24	3.05	3.23	3.04
Augite	3.15	2.96	3.14	2.95

ESTIMATING CONVECTION EFFECTS

No formulas seem to have been developed which can be directly applied to the estimation of the rate of convection circulation. Daly uses an ingenious combination of calculations of (1) the rate of movement of small solid or gaseous spheres, (2) the size which is the limit of application of this formula, and (3) the relative rates for larger spheres.[4] The essential differences between such movement of spheres and convection are, first, that the magma moves

[1] R. A. Daly, "Mechanics of Igneous Intrusion," *Am. Jour. Sci.*, XXVI (1908), 27.

[2] A. L. Day, *et al.*, "Determination of Mineral and Rock Densities at High Temperatures," *Am. Jour. Sci.*, XXXVII (1914), 1.

[3] C. Barus, "High Temperature Work in Igneous Fusion," *U. S. Geol. Surv. Bull.* 103.

[4] R. A. Daly, *Igneous Rocks and Their Origin*, pp. 260–64.

as a larger mass than any sphere considered; and secondly, that the moving mass is not impeded by a liquid of uniform character, but on one side has a more viscous wall, while on the other side there is less resistance and some added tendency to move. On the whole, however, such a calculation may give a fair idea of the order of magnitude of the motion.

The rate of flow of liquids through a pipe may be compared with the rate estimated by this method. In comparison with the pipe, actual convection, though moving a larger volume of liquid, has the friction of only one solid wall. The evident error of estimating by settling spheres alone appears from the fact that a sphere of 10 meters radius gives the same rate in viscous as in less viscous magma. On the other hand, the formula for flow in a pipe gives too much weight to the matter of viscosity. The best idea is probably obtained from a consideration of both calculations and a comparison with the observed rate of convection in lava lakes.

Thermal convection.—On the basis of the data discussed above we may calculate the rate of settling of large spheres by reason of their greater density when cool.

Assumed temperature difference, 100°C.
Main magma specific gravity, 2.70
Cool magma specific gravity, 2.71
Density difference, .01
Final rate of motion of a sphere of 10 meters radius, nearly 1,000 meters per hour[1].

[1] The calculation for this rate of motion is given in detail for this case. Later estimates are made by the same method. If a small sphere sinks in a viscous liquid the final rate of motion is found by a formula of Stokes in *Trans. of the Cambridge Phil. Soc.*, IX, No. 2 (1850), p. 8.

$$x=\frac{2gR^2(d-d_1)}{9V},$$

where R is the radius of the sphere, d_1 the density of the liquid around it, g the acceleration of gravity, and V the viscosity. The largest sphere that will obey this law is calculated by a formula given by Allen in *Phil. Mag.*, L (1900), 324:

$$R^3=\frac{9V^2}{2gd(d-d_1)}.$$

For larger spheres the velocities are proportional to the square roots of the radii

$$\frac{x'}{x''}=\frac{\sqrt{R'}}{\sqrt{R''}}.$$

In the case of thermal convection, the second formula becomes

$$R^3=\frac{9(5)^2}{2(980)(2.70)(.01)}=4.2,$$

Gas-phase convection.—This case is covered by Daly.[1] He assumes from observations on vesicular lava at craters 200 "standard" (1 mm. at surface pressure) bubbles per cubic centimeter. At a depth of 3,000 feet a magma is under a pressure of 200 pounds per square inch. This is a greater pressure than some magmas are subjected to, but it is to be noted that the gas is not only compressed, but more soluble under pressure—a fact which Daly does not seem to consider. There should also be mentioned some thermal effects connected with the separation, reaction, and expansion of the gas bubbles; but too little is known of the effect of these factors on the density to include them in the calculation.

To obtain data comparable with those of other calculations in this paper the following case was selected:

Assumed pressure, 200 pounds per square inch
Assumed vesiculation, 200 "standard" bubbles per cubic centimeter
Magma specific gravity, 2.70
Vesiculated magma specific gravity, 2.638
Density difference, .062
Final rate of motion of a sphere of 10 meters radius, over 2,200 meters per hour.

Double liquid-phase convection.—If an intermediate magma splits into two immiscible liquids, consisting of granite and gabbro phases, the difference in specific gravity might be so great that a rapid separation of the two would occur; but it is not certain that the separation of immiscible globules is accompanied by any pronounced change in the aggregate specific gravity.

Crystal-phase convection.—The effects of the development of crystals should be emphasized, because of the certainty of the

when the viscosity is 5. From this, $R=1.6$ cm. When R is 1.6 cm. and $V=5$, the Stokes formula becomes

$$x=\frac{2(980)(1.6)^2(.01)}{45}=1.1 \text{ cm.}$$

per second. For a sphere of 10 meters radius, the last formula

$$\frac{x'}{x''}=\frac{\sqrt{R'}}{\sqrt{R''}} \quad \text{becomes} \quad \frac{1.1}{x''}=\frac{\sqrt{1.6}}{\sqrt{1000}}.$$

From this $x''=27$ cm. per second. This is 972 meters per hour.

For the greater viscosity, 300, the radius R, of the sphere that will obey Stokes law, is greater, but the final rate of motion of a sphere of 10 meters radius is nearly the same as in the case of the lower viscosity.

[1] R. A. Daly, *Igneous Rocks and Their Origin*, pp. 261–64.

action of crystallization as compared with the separation of the gases and liquids in deep-seated magmas. All magmas crystallize before they are found exposed as deep-seated types, for geological investigation. During the process of crystallization important changes in the aggregate density are likely to occur locally, and the quantitative importance of the change may be estimated. It will be assumed for the calculation that the early crystals are of average density. The specific-gravity increase when crystallization occurs will be 6 to 10 per cent. As outlined above, the viscosity is not enough to interfere with eruption if 40 per cent of the mass is crystalline. To make a conservative estimate—

Assume that 20 per cent of the mass is crystalline.

On the crystallization of one-fifth of the magma the specific gravity of the aggregate will rise from 2.70 to 2.73.

The density difference for any magma is at least .03.

The final rate of motion of a sphere of 10 meters radius is nearly 1,700 meters per hour.

The mineral composition of the early formed crystals may now be included in the calculation. If magnetite crystallizes, the change in specific gravity is estimated as .26 (see Table I); for olivine and augite the change in specific gravity is .19. These, when compared with the change in average gabbro used in calculation (.03), indicate that if the early minerals are magnetite and olivine or augite the specific-gravity difference should be greatly increased, though the change in density of the residual magma would of course be in the reverse direction. With other contributing factors the specific gravity may change as much as .06—twice as much as was assumed. The rate of motion might be even greater than would result from deep-seated vesiculation.

Combination effects.—It is known that two minerals may crystallize together, and that gas may separate from a magma during crystallization; even the separation of immiscible fractions during crystallization is a possibility. These combinations may retard or reinforce the general convection tendency due to simple thermal changes in density.

Use of the formula for flow of liquids through pipes.—If a cylindrical pipe of 10 meters radius be imagined as bent approximately

square, with sides as long as the depth of the magma chamber; and further, if the liquid in one vertical side of the square is kept more dense than the rest, circulation will occur. The formula for viscous or direct flow is[1]

$$Q=\frac{(p_1-p_2)\pi R^4}{8Lv},$$

where Q is the quantity passing a certain place in unit time, (p_1-p_2) the difference in pressure, R the radius of the tube, L the length of the tube, and v the viscosity of the liquid. With a constant radius of 10 meters and the added relation that the length of the tube is 4 times that of the column giving the pressure, the formula reduces to

$$Q=\frac{d_1-d_2}{V}\times\frac{1{,}000^2}{8\times4}\times\pi R^2=\frac{31{,}250\ \pi R^2(d_1-d_2)}{V},$$

where d_1 and d_2 are the specific gravities of the two upright columns.

The rate of flow can be derived from this by the quantity per second per unit cross-section:

$$x=31{,}250\frac{(d_1-d_2)}{V}$$

Comparison of estimates.—Tables II and III show the results in compact form.

TABLE II

ESTIMATED CONVECTION RATE, BY DIFFERENT METHODS, IN METERS PER HOUR

Viscosity (Water at .0115)	Phases	Settling Spheres	Flow in Pipe	Observed*
5	Hot and cool magma	1,000	2,200	....
5	Magma and gas bubbles	2,500	12,000	2,000–5,000
5	Magma and average crystals	1,700	6,600	....
5	Magma and heavy crystals	2,500	12,000	....
300	Hot and cool magma	1,000	40	....
300	Magma and gas bubbles	2,500	220	....
300	Magma and average crystals	1,700	113	....
300	Magma and heavy crystals	2,500	220	....

* R. A. Daly records the convection in a crater lake as 2 to 5 kilometers per hour in "The Nature of Volcanic Action," *Proc. Am. Acad. Arts and Sci.*, XLVII, 76.

The calculated results in other columns are not strictly comparable, as they are based on a pressure of 200 atmospheres, and the convection in the crater may be more active than that 3,000 feet below.

[1] Poynting and Thomson, *A Text-book of Physics* (1902), p. 209.

A recent paper by W. K. Lewis, in *Jour. of Ind. and Eng. Chem.*, VIII, 627–32, gives a good statement of the present methods of calculation. For small velocities the formula for viscous flow applies even to pipes of large diameter.

The relative slowness of motion of sinking crystals is evident from a comparison of the tables. In a sill 1,000 feet thick a large crystal of olivine might settle in a day or two, though it is not probable; small ones would require a few weeks. Convection might carry them down in half an hour, or much less if the viscosity was not at a maximum.

TABLE III

ESTIMATED RATE OF FALL OF SETTLING CRYSTALS OF 4 MM. DIAMETER IN METERS PER HOUR

Viscosity	Mineral	Rate of Motion	Viscosity	Mineral	Rate of Motion
5	Magnetite	132	300	Magnetite	2.+
5	Olivine	25	300	Olivine	0.5
5	Augite	25	300	Augite	0.5
5	Plagioclase (rising)	13	300	Plagioclase (rising)	0.2

THE PROCESS OF SOLIDIFICATION WITH CONVECTION

Form and size and composition of magma.—Small bodies of magma are usually cooled to crystallization too rapidly to permit much circulation. However, the actual limit in size is not to be stated, as the fluidity and duration of crystallization may in case of abundant mineralizers allow an effective convection in a four-foot dike. Thin, tabular masses are unfavorable to any general circulation after intrusion is complete, but no special form or position of the mass seems to prevent all circulation. If the mass is nearly horizontal, settling crystals are more effective than circulation. It has been suggested also that thick, strikingly dome-shaped laccoliths assume their form because of unusual viscosity.[1] In so far as this is so they would be unfavorable to convection. The viscosity of a magma during crystallization depends largely on its composition. Data are not abundant, but indicate that viscosity is greatly reduced by dissolved gases such as water vapor; also that medium to basic magmas are less viscous than acid magmas.

Rate of cooling.—Aside from its size, the temperature of the mass and of its walls affects the rate at which the magma passes

[1] Sydney Paige, "Progressive Increase of Viscosity during Intrusion," *Jour. Geol.*, XXI, 541.

the stage of crystallization. If the cooling is rapid no convection of importance occurs. If the borders are chilled, convection can be active only in the central portions. In considering convection effects then, we eliminate all suddenly chilled phases. There remain many igneous masses of large size in which the process of crystallization extends over a long period.[1]

Where cooling occurs.—At first intrusion cooling progresses from all sides, but, as shown in the discussion of the temperature gradient, later cooling would be largely from the top of the mass and related to surface radiation and ground-water circulation. However, in a mass of laccolithic or batholithic form enough cooling would occur at the sides to establish normally some circulation. Once the current is established it tends to develop in power, the cooling top layer being drawn over to the sides as the side layers sink.

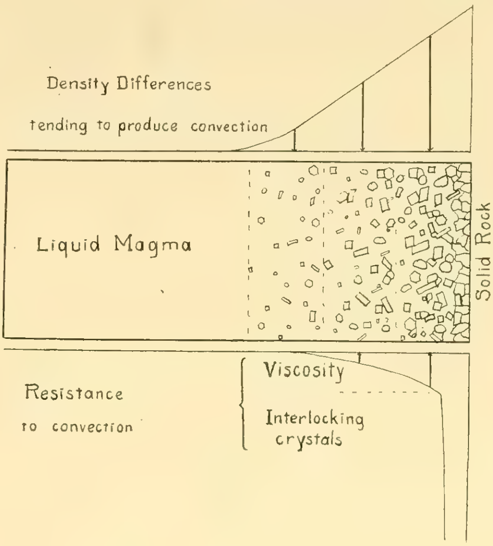

FIG. 1

The column of liquid which is effective in the motion is shown in Fig. 1, representing the zone of cooling near the side of the magma. The active force is much greater than the resisting viscosity up to the point where crystals begin to touch each other. It is greatest in a zone near the solidified wall. As crystallization progresses all the zones move inward. The width of these zones is wholly uncertain, but remembering the wide temperature range through which crystals may be in equilibrium with a magma, it seems probable that 20 meters (used in calculation) is a small estimate for large magma chambers.

[1] R. A. Daly, "Mechanics of Igneous Intrusion," *Am. Jour. Sci.*, XXVI (1908), 25.

The probable size of crystals in convection.—It is suggested[1] that if convection kept a supply of material at hand for the growth of a crystalline border, the largest crystals would be at the borders. This is actually the case in some pegmatitic differentiated dikes and indicates some movement in a thinly fluid magma. However, the mechanics of the process as outlined is not such as to furnish growing crystals a large supply of molecules from the central mother-liquor, though some such action may occur. The crystalline-border phase grows as a result of small crystals becoming caught in a more viscous, less rapidly moving wall. Here the progress of cooling is so advanced that, with the high viscosity, it is not to be expected that large crystals will develop.

The accumulation of crystals.—Most of the crystals, being heavier than the magma, would tend to settle; and though formed during the cooling along the top and sides of the chamber they would probably lodge at the sides and especially along the bottom during the forced circulation inward toward the rising current. Settling would here be entirely sufficient to remove crystals from the current. Similarly the crystals lighter than the magma would have a tendency to lodge along the roof and outer corners. Thus the segregation of minerals depends on gravity and is assisted by convection. It is largely independent of the place where cooling and crystal growth occur.

Orientation of crystals.—When a crystal once lodges in a viscous wall, too viscous to be again involved in general circulation, there may still be sufficient fluidity to allow orientation. The viscous matrix crystallizes, while the magma near it is still in motion, and the crystals would probably be oriented in the direction of the current—in most cases parallel to the walls of the chamber.

Gravity differentiation.—As most of the crystals of an igneous rock are heavier than the magma from which they grow, it will be expected that whichever forms first will segregate toward the bottom. It is only the coincidence of high gravity and early crystallization that results in a strict gravitative arrangement in the resulting rock. However, the general order of crystallization is, as a matter of fact, roughly the order of decreasing specific

[1] N. L. Bowen, "The Later Stages of the Evolution of Igneous Rocks," *Journal of Geology*, Supplement to Vol. XXIII (1915), p. 12.

gravity, and a gravitative arrangement is common. It is not to be expected that large segregations of a single mineral will be other than exceptional, because the cooling progresses in such a way that crystals of several minerals are likely to be growing at once and all settling together on the bottom as well as lodging along the walls. However, the conditions are easily conceived as possible for the formation of magnetite and peridotite near the base, and anorthosite near the top, of a single magma.

The behavior of immiscible liquids may be considered at this time. If the separation of globules occurred in a stationary magma, a gravitative rise and fall would tend slowly toward the separation of the fractions. If the immiscible liquids separate during convection, the smaller fraction, if light, will separate along the top, if heavy, along the bottom, as a fairly distinct layer in logical gravitative position. This layer may crystallize before or after the magma from which it separated, and the first to solidify may be intruded by the other. Abrupt gradations and contacts should be the rule. A small separated layer is likely to escape from the general circulation and is less likely to show a fluxion structure.

Double differentiation.—Thus it is conceived that a magma might differentiate into a series of bands dependent on the order of crystallization and settling, and *at the same time* give a rather abrupt gradation to a separated immiscible rock type—one of radically different composition. This is double differentiation. And the complexity of the sequence in some petrographic provinces is strong indication that two very different processes have been in operation.

Such a suggestion might apply to the occurrence of pyrrhotite at Sudbury which is said to have intrusive relations in some exposures to the main norite; and the norite itself is differentiated in roughly gravitative fashion.

Convection structures.—In discussing convection Pirsson makes the following suggestion: "Probably at first as the liquid moved inward over the floor of the laccolith and became reheated, these crystals [formed in the cooling border zones of the magma] would remelt, giving rise to numerous small spots of magma of a different composition, which would slowly diffuse."[1] It is noteworthy that

[1] L. V. Pirsson, "The Igneous Rocks of the Highwood Mountains," *U. S. Geol. Survey Bull. 237*, p. 188.

the result is, at least temporarily, a heterogeneous condition of the magma. Similar heterogeneity may result from crystals settling from an upper cooling zone into a deeper superheated zone. However, even more important variations in the magma are thought to result from the removal from the cooling zone of crystals of an early period of formation. Thus if a uniform magma had cooled on the outer edges of a laccolith until olivine crystallized, not only would there be convection due to the increased density of the olivine substance, but as the current moved along the floor some olivine crystals would settle out, leaving the liquid to rise in the central part of the mass with a different composition from the average.

It is important to consider in detail the result of this variation in the circulating magma. The material supplied by such a magma to the cooling border zone will differ from time to time and is almost certain to show some alternation because of a lack of rapid diffusion. As different material passed the cooling zone different crystals would be likely to develop, and a layer of different rock would be deposited on the walls and floor, giving rise to bands parallel to the current of magma and parallel to the walls of the chamber.

A further possible cause of alternation of materials deposited may be found in rhythmical activity of the cooling, or intrusion, or gas supply of the magma. Cooling is affected by annual and longer rhythms, but the depth of most of the igneous masses makes it unlikely that the rhythm from the surface would have notable effects. A rhythm in extrusive action is well recognized,[1] and the causes usually assigned to it would apply equally well to intrusive action. The supply of heat, gases, and lava may be distinctly periodic and may be responsible for the alternation of material crystallizing in the cooling zone of the magma.

Banding developed in this way is not likely to be perfectly regular, because of the irregularities of the current, its rise in the center, and its possible tendency to corrode or resorb some bands already deposited. Settling crystals on a large scale would tend

[1] J. D. Dana, *Volcanoes* (Dodd, Mead & Co., 1891), p. 124; Bonney, *Volcanoes*, pp. 274 ff.

to disturb the banding and give a gradation rather than an alternation in composition. It may be suggested also that stoped blocks settling in a magma would disturb such banding. Differentiation, however, is in no way interfered with[1] by the circulation that produces the banding.

SUMMARY

Several lines of evidence indicate that active convection occurred in many large, deep-seated magmas, and the process seems to be mechanically probable. In starting a current in such a mass the increase in density of growing crystals is probably more important than the development of any gas or separate liquid phases; and, added to the effect of simple cooling, the forces seem to be ample. Nearly all the field observations commonly made on igneous rocks may have a bearing on the question; probably first should be placed an alternation of bands of varying mineral composition; the position of the bands and the walls of the chamber; the mineral composition of the bands and the walls; any parallelism of grain and its direction; the form and size of the mass; grain variation near the margin; contact effects; the sequence of rocks formed in differentiation, continuous, double, or broken series; abrupt or gradual variations; intrusive relations between differentiates; gravitative or border position of differentiates; occurrence of one differentiate as a matrix for grains of another; the order of crystallization; signs of mineralizers, and their association with certain differentiates; globular forms.

The idea of convection becomes of practical service to the geologist when related to the banded structure. By it we may find the position of the walls of the chamber. The complexity of some differentiated rock series is best explained by assuming that some of the series developed during convection. Knowing the order of crystallization we can at once decide whether a mineral like magnetite is likely to be in bands near the bottom, or nearer the center, of the magma chamber. Finally a knowledge of the direction of the convection current aids greatly in estimating the extent of such a body of segregated magnetite.

[1] N. L. Bowen, "The Later Stages of the Evolution of Igneous Rocks," *Journal of Geology*, Supplement to Vol. XXIII (1915), p. 16, does not agree.

PERMO-CARBONIFEROUS CONDITIONS VERSUS PERMO-CARBONIFEROUS TIME

E. C. CASE
University of Michigan

Although the "red beds" of the late Paleozoic and other deposits of equivalent age have long been called Permian in North America, evidence is steadily accumulating to show that the true Permian is absent or nearly so, in the United States, and that the beds formerly so called are better regarded as of Permo-Carboniferous age.

Under one or the other of these names there have been included in the eastern part of the United States all the Paleozoic deposits above the base of the Dunkard formation in Pennsylvania, West Virginia, and Ohio, and possibly the upper beds of the Boston and Narragansett basins, the Paleozoic deposits of Nova Scotia and New Brunswick above the base of the New Glasgow conglomerate, and practically all of the red deposits of Prince Edward Island.

In the western part of the United States the same horizon is believed to begin with the base of the Elmdale formation of Kansas and its equivalents, both east and west of the Rocky Mountains.

The discovery of vertebrate fossils belonging to identical or closely related genera and the evidence of fossil plants have led to the suggested correlation of the red beds of Kansas, Oklahoma, Texas, and New Mexico with the Dunkard of Ohio and Pennsylvania, and the isolated deposits carrying vertebrate fossils near Danville, in Vermilion County, Illinois. Such suggestions of correlation, however, do violence to the probabilities indicated by the stratigraphic position of the beds in which the fossils are found. It is the purpose of this paper to point out what seems to be a more rational method of correlation, which will reconcile the evidence from fossils with that from the stratigraphy.

Correlation of widely separated horizons must be largely accomplished upon the evidence furnished by fossils, but, as is

becoming increasingly evident to all workers in stratigraphy as well as paleobiology, fossils must be regarded and interpreted as once living things, and the problem of their distribution is inextricably associated with the problem of their living conditions. The method of evolution is as yet undetermined, but all biologists concede the directive influence of environment when a line is once started, by whatever means it was originated. In other words, evolution of life follows and responds to change, or evolution, in the inorganic environment. If this be true, the beginning of a new geological interval of time is marked by the change in the inorganic world which will lead by slow degrees and a multiplicity of processes to the development, or immigration into a definite area, of new forms of life. The new interval begins with the establishment of new conditions fitted for the new life and may precede by a very considerable period of time the establishment of the new life in such abundance as to be recognized as constituting a new fauna, faunule, or flora. On the other hand, it is very possible that the establishment of new conditions may be almost immediately followed by the introduction of a new fauna or flora, as by immigration. These ideas are in strict consonance with the determination of geological intervals on the principle of diastrophism.

If any progressive criteria can be detected and traced which reveal such a change in the inorganic world, then the evidence of the organic world may be better interpreted and even in some measure anticipated. Changes in the inorganic world are in general more obvious under terrestrial conditions than under marine, but a change from marine to terrestrial conditions would be the most obvious of all.

The more evident and violent effects of diastrophism are readily detected and their results easily interpreted, but where the change is a slow and gentle one with slight disturbance of the rock layers and, as in a case of slow elevation, with a resultant destruction of the surface beds and sparse deposition of terrestrial sediments, the problem becomes far more intricate. In such a case it is sometimes necessary to turn to more obscure and commonly neglected factors, such as the climatic alteration resulting from change of altitude and exposure of large areas of land.

It is just this factor of climatic change that the author proposes to use in the interpretation of the change of environment in late Paleozoic and as a basis for the correlation of "Permo-Carboniferous conditions" as opposed to a correlation of a certain group of beds within definite stratigraphic limits. "Permo-Carboniferous conditions," as here used, involves the idea of an interval of time, but not of the same duration in all areas where such conditions prevailed, for, as will be shown, the conditions were developed progressively across a large area and the base of the deposits governed by such conditions cut obliquely across the stratigraphic column. In the case here discussed the shape of the deposits so governed is that of a flat wedge, for the conditions persisted where they were

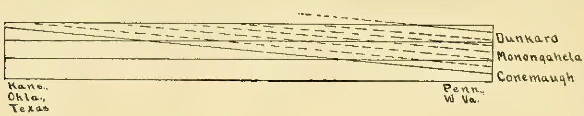

FIG. 1.—Diagrammatic illustration of the relation of "Permo-Carboniferous conditions" to the late Paleozoic stratigraphy. No account is taken of the breaks or the present geological structures. The dashed area indicates "Permo-Carboniferous conditions."

first established and the progress of the conditions led to ever thinner deposits toward the outer limit (see Fig. 1). It is conceivable that under other circumstances a uniform set of conditions might pass across a large area as a wave, and the resultant deposits would then be detected in the stratigraphic column as a band of greater or less thickness oblique to the normal bedding-plane.

As shown in the abbreviated correlation table below, the Dunkard with its typical Permo-Carboniferous flora, fauna of invertebrates, and single characteristic vertebrate (*Edaphosaurus*) is by all commonly accepted canons of correlation and by its stratigraphic position the very approximate equivalent of the Wichita-Clear Fork beds of Texas, but both red beds and Permo-Carboniferous vertebrates are found far below this horizon in both Pennsylvania and West Virginia. In Pennsylvania, Raymond found vertebrates closely similar to those occurring in Texas in the Pittsburg Red Shale, 500 feet below the top of the

ABBREVIATED CORRELATION TABLE OF THE LATE PALEOZOIC

Texas	Oklahoma	Kansas	Indiana	Pennsylvania and West Virginia	Massachusetts	Rhode Island	New Brunswick
Absent or red deposits in the panhandle	Quartermaster and Greer	Cimarron		Dunkard	Roxbury conglomerate (Squantum tillite)	Dighton conglomerate	New Glasgow conglomerate
Double Mountain	Woodward	Wellington					
Clear Fork	Blaine	Marion					
Wichita*	Enid	Chase					
		Garrison	Merom sandstone				
		Waubunsee					
Cisco	Ralston (Chandler)	Shawnee	Coal VIII	Conemaugh	Dorchester slate	Rhode Island formation	Shulie formation

*Permo-Carboniferous conditions began approximately at the time indicated by the heavy lines in the table.

Conemaugh. In West Virginia, Hennen found the cast of a bone comparable only with *Pareiasaurus* in red shales about 200 feet below the base of the Monongahela series.

Dr. I. C. White has long contended that the sudden appearance of the red sediments in the Conemaugh marks the beginning of a new geological period with changed conditions of environment and sedimentation. The red deposits continue in Pennsylvania and West Virginia more or less dominantly to the top of the Dunkard. Farther to the north the red sediments, tillites of the Boston basin, the New Glasgow conglomerate and the red conglomerates, and shales and sandstones of Prince Edward Island are certainly well up in the late Paleozoic. Sayles and Mansfield have demonstrated the glacial origin of the Squantum tillite, and Bell has shown that the New Glasgow conglomerate is due to an elevation somewhere to the southeast.

These local proofs of elevation are but contributory evidence of the commonly accepted elevation of the whole eastern part of North America, probably as a continuation of the same movement which formed the Hercynian chain somewhat earlier in Central Europe. The elevation of North America which began on the eastern side was gradually extended to the west, as is shown by the progressive disappearance of the Mississippian sea and the Pennsylvanian coal swamps in that direction.

The elevation was attended by a gradual change in climate; instead of gray and black shales and white sandstones the prevailing deposits were colored red by the oxidation of the iron under the influence of a less equable climate, as seasons of relative drought and humidity succeeded each other.

As this climatic change migrated toward the west only slowly, red sediments were formed at progressively higher and higher levels. In western Kentucky, Indiana, and Illinois the conditions necessary for the formation of red beds did not arrive until after the highest sediments now preserved had been formed, or only thin deposits were formed which have since been removed by erosion. That the surface on these regions was dry land by the time "Permo-Carboniferous conditions" (formation of red beds) had reached them is suggested by the mode of occurrence of the vertebrates in Illinois and the Merom sandstone in Indiana.

Beyond the elevated region of Missouri the upper Pennsylvanian and Permo-Carboniferous rocks of Kansas are limestones and gray to black shales, but farther south the Permo-Carboniferous beds of Oklahoma, Texas, and New Mexico are red. These beds lie above the Missourian of Missouri and Iowa which extend well up toward the top of the Pennsylvanian, as developed in Pennsylvania and West Virginia, certainly much higher than the first appearance of red beds in the Conemaugh series in those states.

The appearance of red beds is generally accepted as evidence of a decided climatic change and it is also generally accepted that this change in the late Paleozoic was largely the result of an elevation of the continent which began in the eastern side and progressed toward the west, though other causes, as a change in the amount of CO_2 in the air, very probably had some part in the final result.

As stated above, red beds appear at successively higher levels toward the west. Detailed evidence for this will be given in a forthcoming monograph in the publications of the Carnegie Institution of Washington.

As the uplift affected regions farther and farther to the west, the climate altered progressively in the same direction and the resultant changes in physiography, hydrography, and vegetation compelled an alteration of the environment which permitted the migration of the Permo-Carboniferous reptilian-amphibian fauna with but little morphological change.

This environment remained fixed in the east as it spread westward, resulting in a wedge-shaped series of beds which can be correlated as formed under "Permo-Carboniferous conditions" from the observed effects produced by climatic factors. The wedge shape of this series causes it to extend deeply into the Pennsylvanian series (to middle Conemaugh) in the east and to involve only the true Permo-Carboniferous in the west. The development and migration of the vertebrate life were governed, not by the passage of geological time, but by the development and spread of the peculiar environment.

The occurrence of Permo-Carboniferous reptiles and amphibians much lower in the stratigraphic series on the east than on the west is no longer a puzzle. The animals appeared with the environment and migrated with it. They occur strictly within the time and

limits of "Permo-Carboniferous conditions" at every place where they are known.

The sequence in the evidence of the progressive development of the red bed westward is broken in two places by the elevation at the Cincinnati anticline and at the elevation in Missouri. An effort has been made to trace the beds around these elevations, but as yet with indifferent success. The breaks are in part due to the effects of erosion removing all traces of Permo-Carboniferous deposition and in part to the fact that these lands were elevated above the plane of deposition before the climatic migration had reached them.

An apparent conclusion from the premises here stated is that the Permo-Carboniferous vertebrate fauna originated in the eastern part of North America and migrated westward. This the author is not yet entirely ready to accept, and yet he is strongly impelled toward that conclusion by the facts that the earliest known reptile was discovered in the Allegheny series, at Linton, Ohio; that typical Permo-Carboniferous vertebrates appeared in middle Conemaugh time in Pennsylvania and West Virginia, and that typical Pelycosaurs occur in the red beds of Prince Edward Island at a stratigraphic level much lower than those of Oklahoma and Texas.

The theses of this paper are:

1. That environment is the determinant factor in the development and spread of a fauna.

2. That an environment favorable to a certain group may develop and migrate, involving different levels of one or more geological epochs.

3. That a fauna or flora may be correlated as belonging within the limits of such an environment independent of stratigraphic levels.

4. That the limits of such an environment may be detected by various lines of inorganic evidence. In the case of the development and spread of "Permo-Carboniferous conditions" the effect of climate furnishes the observable limits.

Further evidence for the statements made in this paper and more extended treatment of the subject will be given in a monograph of the Carnegie Institution of Washington dealing with the environment of life in the late Paleozoic.

NOTES ON THE GEOLOGY OF EASTERN GUATEMALA AND NORTHWESTERN SPANISH HONDURAS[1]

SIDNEY POWERS
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CONTENTS

ILLUSTRATIONS

INTRODUCTION

The geology of Central America between the Isthmus of Tehuantepec and the line of the proposed Nicaragua Canal has been known only from the researches of Dr. Karl Sapper. These observations through a number of years have covered a vast amount of territory in a general way.[2] A brief examination of the Atlantic

[1] Published by permission of the Director, United States Geological Survey.

[2] K. Sapper, "Über Gebirgsbau und Boden des nördlichen Mittelamerika" (with geological map of Guatemala), *Peterm. Mitt.*, Ergänzungsheft 27, Heft 127, 1899; "Gebirgsbau und Boden des südlichen Mittelamerika" (with geological map of

Coast region between Trujillo, Spanish Honduras, and Livingston, Guatemala (Fig. 1), forms the subject of the few notes on the geology which are here presented. The petrography of the igneous rocks collected in Honduras is described in an accompanying paper by Professor Wilbur G. Foye, of Middletown, Connecticut.

Geologic investigations in the portion of Central America examined are conducted with difficulty owing to the primitive means of transportation inland beyond the coastal banana-plantation railroads and to the dense growth of tropical vegetation. Satisfactory exposures are confined to stream valleys. Also a scarcity of fossils in pre-Tertiary strata makes correlation and age determination exceedingly difficult. In Honduras fossils of Triassic and Cretaceous ages have been described; in Guatemala strata of Carboniferous (probably Pennsylvanian or upper Mississippian), Cretaceous, Eocene (?), Oligocene, Pliocene, and Pleistocene ages are known.[1] A lack of fossils and of detailed knowledge of the metamorphic rocks has made it impossible to determine whether they are in large part merely a metamorphosed portion of the Carboniferous or of an earlier Paleozoic system, as is suggested by the writer, or whether they are of pre-Cambrian age, as supposed by Sapper.

GENERAL GEOLOGY

Eastern Guatemala and northern Honduras lie on the south and southeast sides of the V-shaped Gulf of Honduras in latitudes 15° to 17° N. Commencing at the north the larger portion of the peninsula of Yucatan (Fig. 1), with the exception of the Cockscomb Mountains (an outlier of Paleozoic rocks in British Honduras), is composed of horizontal sediments of late Tertiary age which

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Honduras and Central America), *ibid.*, Ergänzungsheft 32, Heft 151, 1906; "Grundzüge der physikalischen Geographie von Guatemala," *ibid.*, Ergänzungsheft 24, Heft 113, 1894–95; "Die Alta Verapaz" (Guatemala) (with geological map of part of Guatemala), *Mitt. Geogr. Gesell. Hamburg*, XVII (1901), 78–224; "La geografía física y la geología de la península de Yucatán" (Chiapas and Tabasco states only), *Bol. Inst. geol. México*, No. 3, 1896; A. Dollfus et E. de Mont-Serrat, *Mission scientifique au Mexique et dans l'Amerique Central*, *Géologie*, Paris, 1868; E. Suess (de Margerie), *La Face de la terre,* III (3) (1913), 1264–74.

[1] Bailey Willis, *Index to the Stratigraphy of North America*, U.S. Geol. Surv., Professional Paper No. 71, 1912.

form a region of little relief. A belt of gently folded Cretaceous and Oligocene strata, principally limestones with an east-west trend, separates the lowlands on the north from the high mountain ranges in the south. The relief of the mountains carved in rocks

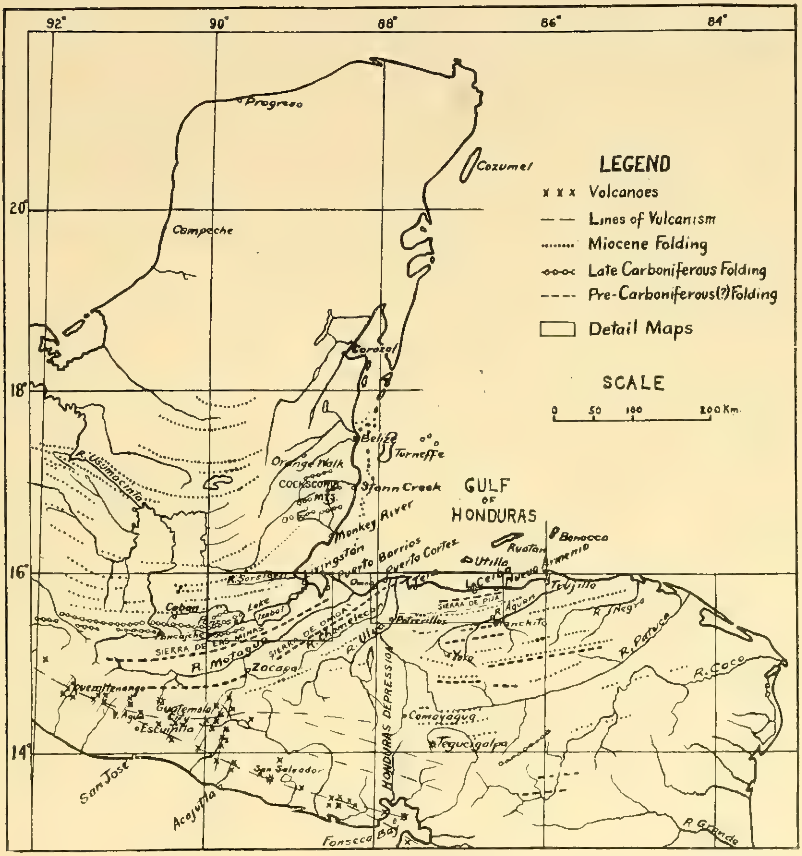

Fig. 1.—Tectonic lines in Honduras and Guatemala, modified from Sapper (Eighth International Geographical Congress, 1904 [Washington, 1905], Fig. 1).

of these ages is of the order of 1,000 to 2,000 feet. Mountains of metamorphic and intrusive rocks forming conspicuous parallel ranges extend from southwestern Mexico and central Guatemala through northern Honduras and meet the coast at an angle on the south side of the Gulf of Honduras. The relief of the mountains

is 1,000 to 4,000 feet and the height of some more than 5,000 feet.[1]

Plateaus and irregular ridges of low relief, but with elevations of 3,000 to 4,000 feet, are found west and southwest of the mountains composed of metamorphic rock. This region is composed of early Tertiary or possibly late Mesozoic volcanics.[2] In places folded sedimentary rocks appear with the volcanics. Farther inland and nearer the Pacific Coast the ridges of folded volcanics give way to broad plateaus that are 3,000 to 4,000 feet above sea-level and are separated more or less completely from one another by rims of low hills. The plateaus slope gently toward the east. Young, deep gulches are rapidly dissecting the plateau surfaces. Exposures thus made show that the surfaces were formed in an earlier cycle of erosion by overloaded streams under conditions of aridity and that deep incision is now taking place for the first time. The summit of the plateau forms the continental divide—a volcanic plateau on which stands Guatemala City at an elevation of 4,900 feet.

On the Pacific slope in Guatemala the high plateaus are bounded by a row of active and recently extinct volcanoes which rise in many cases directly to elevations of 10,000 to 13,513 feet from the low plain that forms the coast. The alignment of the volcanoes is parallel to the coast and diverges sharply from the trend of the older mountain ranges. The plain at the coast is composed of volcanic ejectamenta and shows no signs of uplift; hence it would not be called a coastal plain according to some definitions of that term. It is so level that 20 miles inland, at Santa Maria, the elevation is only 416 feet. From here the surface gradually rises to an elevation of 1,100 feet at Escuintla, 27 miles inland. Only 40 miles inland the dormant volcano Agua, near Escuintla, is 12,140 feet high.

[1] Elevations of 8,000 feet for Congrejal and Bonita peaks, near La Ceiba, Honduras, as given on a chart of the U.S. Coast and Geodetic Survey, evidently should be 4,000 feet.

[2] Vulcanism is thought to have begun during the Eocene in Mexico (J. G. Aguilera, *Compte Rendu* [10th Int. Geol. Cong., Mexico, 1906], p. 1157) and to have been in progress during the Oligocene in Nicaragua (C. W. Hayes, quoted by Sapper, *Zeit. Ges. f. Erdkunde* [Berlin, 1902], p. 513).

Rainfall and humidity have everywhere an important bearing on vegetation and therefore on surface features. The high plateaus behind mountains which catch all the moisture suffer from aridity and afford scant vegetation. At lower elevations, but again in the lee of the mountains, there are deserts, as at Zacapa, supporting only cactus. Near the sea both coasts receive an overabundance of rainfall with accompanying great humidity. On both sides of the Isthmus the northeast trades are the prevailing winds, but on the Pacific Coast the winds are variable except during winter of the northern latitudes.

Statistics for an average year show rainfall on the Pacific Coast (elevation 600 feet) of 240 inches; at Guatemala City (elevation 4,900 feet) of 60 inches; at Quirigua (elevation 240 feet), 57 miles from Puerto Barrios, but behind a mountain range, of 99 inches; at Panzos (elevation 50 feet), 100 miles inland, of 115 inches; at Puerto Barrios, on the Atlantic, of about 200 inches. The rainy season on the Pacific Coast is May 15 to October 15, on the Atlantic Coast June 15 to August 15 and September 15 to February 15. The best weather in Guatemala and Honduras as a whole is therefore in the winter and spring of the northern latitudes, and only during this dry season can geologic work be carried on satisfactorily in the coastal regions.

GEOLOGY

Spanish Honduras.—Northern Honduras consists of two mountain ranges of the metamorphic series, each with many subsidiary branches. The first of the parallel ranges forms a portion of the boundary line between Guatemala and Honduras (Figs. 1 and 4) and is variously known as the Sierra de la Grita, Sierra de Merendon, Sierra del Espiritu Santo, and the Sierra de Omoa—the Omoa Mountains. This range lies for a distance between the Motagua and Chamelecon rivers (Fig. 2), but east of the broad Chamelecon-Ulua lowlands it reappears in Punta Sal and in the Bay Islands (Utilla, Ruatan, and Bonacca). The second range, Sierra de Pija (Fig. 1), lies west of the Ulua River between the various short streams on the Atlantic shore and the Aguan River (Yoro-Olanchito) valley. This range extends into the sea east of Trujillo.

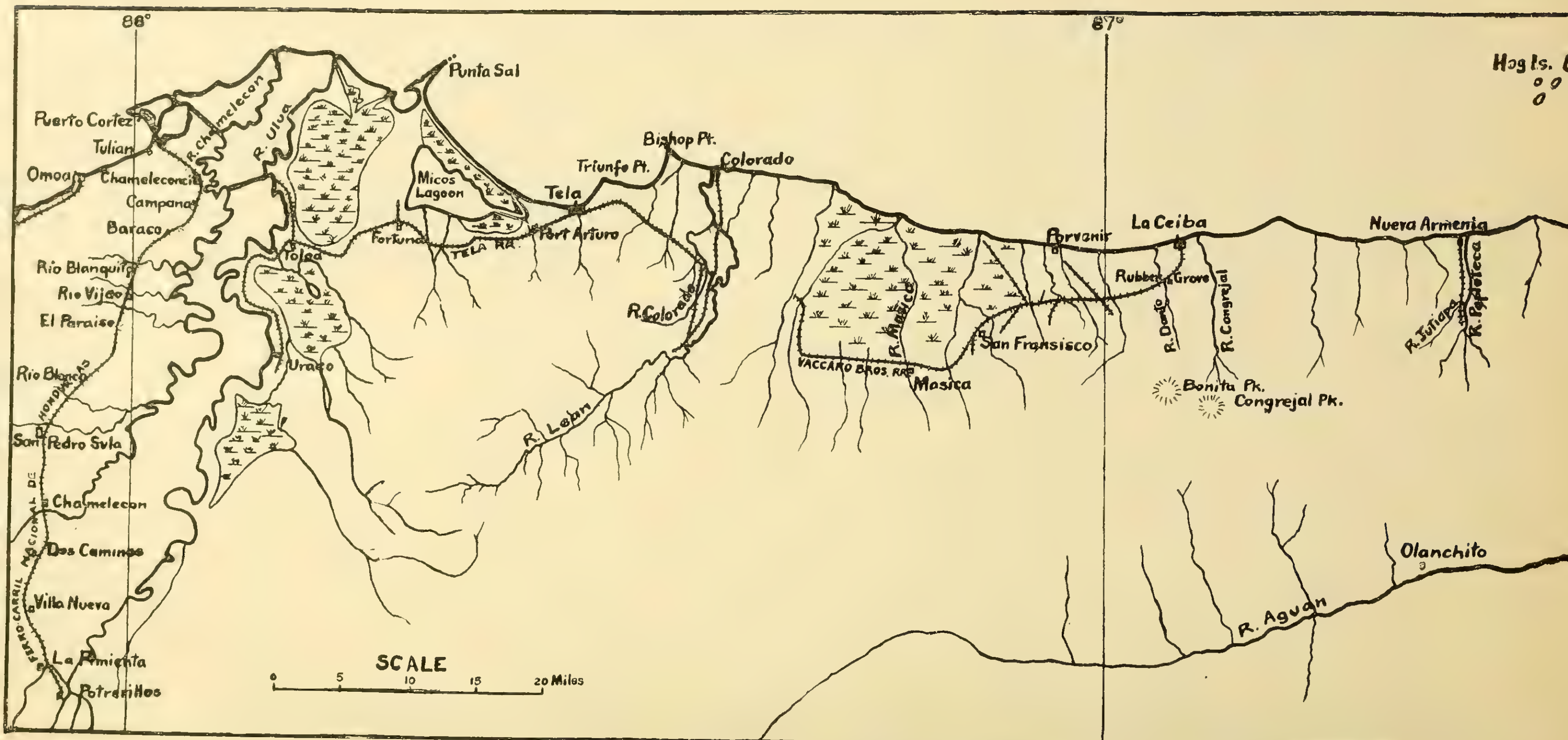

FIG. 2.—Map of the northwestern portion of Honduras

Considered as a whole, the Omoa Range consists principally of slates, schists, quartzites, and limestones, while the Sierra de Pija is composed of mica schists and quartzites intruded by granodiorites, diorites, and tonalites.[1] The igneous rocks as a whole may represent phases of a single large batholith. The intrusions have a lineal arrangement in a N. 50°–80° E. direction and occupy the region between the sea and the summit of the range. Basalt of Tertiary or Quaternary age occurs in the Sierra de Omoa at Chameleconcito, near Puerto Cortez, and on the island Utilla. Sandstones and conglomerates of late Tertiary age are found along the shore cliffs between Puerto Cortez and Omoa.

The age of part of the metamorphic rocks is known to be Paleozoic; the age of the remainder is thought to be Paleozoic. Carboniferous fossils were found by the writer in metamorphosed, horizontally bedded limestones in the hills west of Puerto Barrios, Guatemala, not far from the line of strike of the marbles in the Sierra de las Minas, north of the Motagua River valley, and of other metamorphic rocks. If the metamorphic rocks are of Paleozoic age the batholithic intrusions must have appeared during the subsequent folding, presumably at the close of the Paleozoic.

Along the continuation of the Sierra de Omoa at Punta Sal, north of Tela (Fig. 2), black slates striking N. 70° E. and dipping 55° N. form a prominent ridge. The main range of the Sierra de Omoa consists of mica schists, quartz schists, and quartzites, as seen in the exposures along the Ferrocarril Nacional de Honduras between Chameleconcito and Baracoa. Limestone appears at Baracoa, where springs of cool carbonate water have built large calcareous tufa terraces. At Rio Vijao marble has been quarried for ballast. The marble may be seen as far as Rio Chaloma (El Paraiso), but is replaced by tonalite or granodiorite from this point to San Pedro Sula. No observations were made on the Sierra de Omoa near the Guatemala boundary, but at Quebradas de Oro, in Guatemala, placer gold is mined hydraulically, the country rock being hornblende schist penetrated by quartz veins.

[1] Described in "Notes on Collection of Rocks from Honduras, Central America," by Wilbur G. Foye, in this issue of the *Journal of Geology*.

Gently folded Tertiary or possible early Pleistocene sand, gravel, and clays are exposed in sea cliffs 40 feet in height between Tulian, south of Puerto Cortez, and Omoa. Bedding in these sediments is on the whole regular, but within individual strata there is cross-bedding. The gravel is composed in part of bowlders 3 inches to a foot in length, packed together as if deposited in streams and not in the sea. No shells or fragments of wood were found, although in somewhat similar beds at Livingston, Guatemala, casts of marine shells of Pleistocene (?) age were found.

Olivine basalt composes a number of small, rounded hills one mile south of Chameleconcito and near the National Railroad. The hills are of the typical form developed on weathered *aa* flows. A recent, perhaps Pleistocene, age must be assigned to the basalt flows here and on Utilla Island.[1] Hot springs, apparently connected with the same vulcanism, are very common along the coastal region from the Gulfete (Rio Dulce), Guatemala, to Trujillo, Honduras, especially near the foot of the mountains between Tela and Trujillo.

Between the Sierra de Omoa and the Sierra de Pija in the vicinity of the National Railroad tonalites appear in low hills north and west of San Pedro Sula. This city is built on a broad gravel fan extending from the mountains on the south. In these mountains the contact effect of diorites with metamorphosed schists may be seen. A tonalite similar to that exposed near San Pedro Sula outcrops in the Ulua River and in the hills near Uraca, a native village at the present southeastern terminus of the Tela Railroad, 36 miles by rail from Tela. From Uraca eastward diorites, tonalites, and other igneous rocks invade schists and quartzites, as described by Professor Foye.

[1] The distribution of the basalt is in accord with the researches of A. Bergeat ("Zur Kenntnis der jungen Eruptivgesteine der Republik Guatemala," *Zeit. d. d. Geol. Gesell.*, XLVI [1894], 131–57), who shows a conspicuous arrangement of volcanics according to types in the few specimens of Guatemalan volcanics examined. Basic and acidic types, basalt and rhyolite, are practically confined to the region east of the Pleistocene volcanoes, while the intermediate type, andesite, is the conspicuous component of the surficial rocks of the Pacific volcanoes. A predominance of volcanics of an intermediate type on the immediate borders of the Pacific Ocean is also suggested by B. Koto to hold true in Japan (*Jour. Geol. Soc. Tokyo*, XXII [1915], 124; XXIII [1916], 127).

South of San Pedro Sula, at Chamelecon, intensely folded mica schist is exposed. The foliation strikes N. 80° E. South of Chamelecon and of the Chamelecon River, crystalline limestones, in which no trace of bedding or of fossils were found, extend from Dos Caminos to Potrerillos, the terminus of the National Railroad. One mile south of La Pimienta the limestone is overlain by volcanic ash and by lava flows. Sapper maps the limestone as Upper Cretaceous.[1]

In the Sierra de Pija between the Ulua River and Trujillo igneous and metamorphic rocks were found in every stream examined. Tonalites and porphyries are the most common igneous rocks, with paleovolcanics on the west, especially in the vicinity of La Ceiba and in the Congrejal Valley south of La Ceiba. The metamorphic rocks of sedimentary origin are schists and slates with cleavage striking N. 60° E. parallel to the range.

The Bay Islands, lying 20 to 35 miles off the north shore of Honduras, consist of three large islands, Utilla, Ruatan, and Bonacca (Fig. 1), with several small islands and cays. While the axes of the large islands are not quite parallel, they are all part of the Sierra de Omoa. Historically the islands are known from the fact that Columbus landed on Bonacca on his fourth voyage in 1602, and from the fact that they are inhabited by English-speaking people and were not ceded to Honduras by Great Britain until 1860.

Bonacca Island is 10 miles long and 2½ miles in maximum width, and the highest elevation is 1,200 feet. According to Sapper the island is composed of mica schist with serpentine (marble?) on the western end. Ruatan is 33 miles long, 3 miles wide, and the highest elevation is 800 feet. Sapper found mica schist with some crystalline limestone and amphibolite on the island.[2] Utilla is 7½ miles long and 2½ miles wide. The western two-thirds of the island is composed of coral reefs, lagoons, and swamps, but the eastern third consists of a rolling upland averaging 40 feet in height, surmounted by Pumpkin Hill, 290 feet high, and Stuert Hill, 169 feet high. The rolling surface is underlain by olivine basalt flows.

[1] *Peterm. Mitt.*, Ergänzungsheft 32, Heft 151 (1905), geologic maps.

[2] *Ibid.* (1905), pp. 17–18.

Stuert Hill consists of olivine basalt and agglomerate, Pumpkin Hill of palagonite tuff of basaltic composition containing fragments of coral reef limestone. The tuff with its inclusions is indistinguishable from that which composes the well-known cones on the island Oahu, Hawaiian Islands, near Honolulu. Stuert Hill was evidently

Fig. 3.—Relief map of Guatemala, showing the long Polochic–Lake Izabal Valley on the north, Motagua Valley in the center, the row of volcanoes facing the Pacific, and the broad plain at the Pacific Coast. The International Railroad runs from Puerto Barrios, on the Atlantic, up the Motagua Valley, past Guatemala City in the high plateaus to San Jose, on the Pacific. A branch line runs from Santa Maria northwestward to the Mexican boundary.

a center of volcanic activity in Quaternary time—perhaps the principal one for the island—while Pumpkin Hill probably resulted from a local submarine eruption breaking through coral reefs. Small coral reefs are found on the summit of Stuert Hill, and a small elevation called Brandon Hill is composed entirely of limestone. The age of these reefs is unknown, but is probably quite

recent. The only evidence of pre-Tertiary rocks on the island found by the writer was a block of mica schist in the cemetery. The Hog Islands, near Nueva Armenia, at the mouth of the Paploteca River, are composed, according to Sapper, of mica and graphite schist.[1]

Guatemala.—A relief map of eastern Guatemala (Fig. 3) shows two remarkable east-west valleys, the Motagua and the Polochie–Lake Izabal, separated by the Sierra de las Minas range, which follows a curve slightly concave to the north. The region south

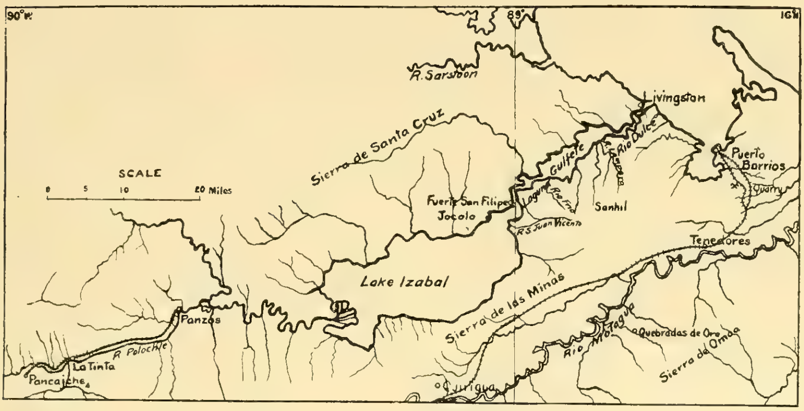

FIG. 4.—Map of the eastern portion of Guatemala

of the Motagua Valley is formed by the continuation of the Sierra de Omoa. The Sierra de las Minas is composed of sedimentary and metamorphic rocks of Carboniferous and of pre-Carboniferous age. North of Lake Izabal the rugged country of gradually diminishing relief is underlain by folded limestones of Cretaceous age.

Fossils of Carboniferous age were collected by the writer in two localities: in the mountains west of Puerto Barrios along the pipe line to the reservoir which supplies that town, and on the line of the Panzos Railroad, along the south bank of the Polochie River near Pancajche, the western terminus of the line (Fig. 4). At the former locality poorly preserved fossils were found in weathered surfaces of a massive, bluish limestone which is metamorphosed and cut by innumerable calcite veins averaging one-quarter of an

[1] *Peterm. Mitt.*, Ergänzungsheft 32, Heft 151 (1905), pp. 17–18.

inch in width. The age of the fossils was determined by Dr. E. O. Ulrich as probably Upper Mississippian or Lower Pennsylvanian. Excellent exposures of the same rock were seen in a quarry 7 miles inland from Puerto Barrios along the old line of the International Railways of Central America. The Pancajche fossils, a large species of *Fusulina*, of Pennsylvanian age according to the determination of Professor P. E. Raymond, were found in dense, bluish limestone interbedded with slate and with mica schist dipping 40°–80° S. to S.E. These rocks belong to the Santa Rosa formation of Sapper.[1]

The Sierra de las Minas range is mapped by Sapper[2] as being composed, from south to north, of serpentine, crystalline schist and gneiss, granite (in part of range), Santa Rosa formation schist of Carboniferous age (as at Pancajche), and Carboniferous limestone. The belt mapped as serpentine coincides with a belt of very good quality white, crystalline marble which composes the south flank of the mountains and is now being quarried on an extensive scale 15 miles northwest of Zacapa (Fig. 1). The marble is said to be equal in quality to any in the United States.

An unconformity is supposed to exist on the north side of the mountains between the crystalline rocks and the fossiliferous Santa Rosa formation schists. The evidence of this unconformity is stated by Sapper to be the presence of occasional pebbles of crystalline schist as large as nuts in the Santa Rosa schists.[3] On the strength of this evidence Sapper places the crystalline schists in the pre-Cambrian, although he admits that the rocks cannot always be distinguished. Confirmatory evidence of the existence of this unconformity is needed, for the degree of metamorphism of the rocks increases from north to south in both Guatemala and Honduras. Mountain-building movements at the close of the Paleozoic will account for all the variations in the degree of metamorphism of the Paleozoic rocks. Intensely metamorphosed and recrystal-

[1] *Mitt. Geogr. Gesell. Hamburg*, XVII (1901), with lists of fossils collected by him.

[2] *Peterm. Mitt.*, Ergänzungsheft 27, Heft 127, 1899; *Mitt. Geogr. Ges. Hamburg*, XVII (1901).

[3] *Mitt. Geogr. Gesell. Hamburg*, XVII (1901); Dollfus et Mont-Serrat (*op. cit.*) also report an unconformity.

lized rocks such as would be expected in a pre-Cambrian terrane are absent.

A block of almost horizontally bedded uppermost Oligocene limestone forms a flat-topped ridge 3 miles wide at Livingston. This block was probably faulted down against the Carboniferous limestones of the Puerto Barrios reservoir during the late Miocene folding of the region, but its present width may have been determined by later movements. Through this block the Rio Dulce cut a narrow gorge during the latest uplift of the region; the gorge is 300 to 500 feet in width and 175 to 300 feet in depth. The fauna collected in the walls of the gorge consists principally of corals and oysters, but it is not a coral-reef formation.[1]

Oligocene limestone, which may be called the Rio Dulce limestone, is undoubtedly more widespread in northern Guatemala than has hitherto been supposed. Limestones forming low hills on the north shore of Lake Izabal at Jocolo (Fig. 4) with a N. 50°–80° E. strike and apparently vertical dip resemble the Rio Dulce limestone lithologically and in obscure fossil content. Likewise blocks of limestone collected at Fuerte San Filipe, at the entrance to Lake Izabal, show spines and other fragments of echinoids on weathered surfaces and are probably part of the same formation. As Sapper mapped the Livingston–Sierra de Sta. Cruz region as Upper Cretaceous,[2] part of his extensive Cretaceous area may be of Tertiary age.

Slightly consolidated quartz gravels and clays containing casts of marine shells of Pliocene or Pleistocene age are found in the lowest of the terraces on which Livingston is built. These gravels are probably a part of the formation which is exposed along the Omoa and Tulian shore of Honduras, as already described. No evidence of folding was seen, however, in the Livingston exposures. Fossiliferous white clays containing chert pebbles and interbedded black lignite seams of Pleistocene or possible Pliocene age underlie the region between Sanhil (Sierra de las Minas), the Rio Dulce

[1] Dr. T. W. Vaughan, of the U.S. Geological Survey, identified the fragmentary fossils as resembling those of the Emperador limestone of the Canal Zone (the Empire limestone of R. T. Hill).

[2] *Peterm. Mitt.*, Ergänzungsheft 27, Heft 127 (1899), geologic map.

limestone ridge at Livingston, and Lake Izabal (Fig. 4). The fossils collected were identified by Dr. Paul Bartsch as the fresh-water gastropod *Sphaeromelania lacustris* Morelet (?).[1] Lignite beds 2 to 3 feet thick occur in several streams emptying from the south into the Gulfete and Laguna between Rio Dulce and Lake Izabal—Rio Lampara, Rio Frio, Rio Juan Vicente—and lignite beds are reported near Livingston east of the Rio Dulce limestone. The white clays and lignite beds may have a thickness of a few hundred feet. They are folded, dips as high as 8 degrees being observed. Rounded chert bowlders, apparently similar to those associated with these clays, are reported by Sapper to be associated with chalk and limestone in northern Yucatan and in British Honduras between Belize and Orange Walk.

British Honduras.—Southern British Honduras is underlain by a continuation of the Oligocene Rio Dulce limestone and of the Cretaceous limestone of Guatemala. Prominent ridges of limestone, probably the Rio Dulce limestone, form the hills along the Sarstoon River near the southwest corner of British Honduras and at Punta Gorda, British Honduras, on the coast. North of Punta Gorda the flat shore is bounded by the most extensive barrier reef in the Atlantic Ocean. Behind the cays and reefs is the closed inland passage up the Yucatan Coast with narrow channels through the reefs. Farther north the large island Cozumel, composed of limestone reefs elevated 10 to 30 feet above sea-level, lies off the flat, monotonous coast of Yucatan.

Geological observations on British Honduras have been made by Sapper and by others.[2] The Cockscomb Mountains of British Honduras are described as a horst about 45 miles in diameter with mountains as high as 3,050 feet. Sapper speaks of granites and quartz porphyries, argillaceous schists, quartzites, and crinoidal Carboniferous limestone striking in a northeast to east direction. North of these mountains and extending over the large department Peten, Guatemala, late Tertiary limestones are so soluble that the

[1] Collected near Rio Frio. From shells eaten by the Indians Dr. Bartsch identified *Euglandina carminensis* Morelet, *Sphaeromelania corvina* Morelet, *S. glaphyra immenis* Morelet, and *S. glaphyra* Morelet.

[2] *Peterm. Mitt.*, Ergänzungsheft 27, Heft 127, 1899; E. Suess (de Margerie), *La Face de la terre*, III (3) (Paris, 1913), pp. 1264–74.

drainage is largely underground. One cave on the Belize River is said to rival the Mammoth Cave in size.

RECENT CHANGES OF LEVEL

A stillstand of the Central American coast is scarcely possible, as is indicated by the frequent earthquakes which disturb the country. In Guatemala perceptible earthquakes are frequently of daily occurrence on the high plateau, as at Guatemala City, but are relatively rare on the Atlantic shore. Changes of level are recorded along the Atlantic shore in elevated coral reefs and terraces and in drowned valleys.

Evidence of uplifts are seen on Utilla Island. A coral reef covers the summit of Stuert Hill, 169 feet high, and less conspicuous reefs are found at lower levels, the lowest being a recently elevated reef 3 feet high on the eastern side of the island. The same recent uplift may account for the narrow bench in front of a wave-cut cliff of basalt on which the town Utilla has been built. Extensive coral reefs and cays surround Utilla Island, but they nowhere skirt the mainland of Honduras or Guatemala in the regions examined.

Lagoons fronted by a continuous sandy beach skirt the northern coast of Honduras. The beaches are tied to rocky headlands and to river deltas, but they extend across the mouths of rivers in the form of bars 2 to 6 feet in depth. A normal tide of only about one foot and littoral currents from west to east have favored the construction of the bars. No vertical movements are connected with their formation.

Elevated benches obscured by dense vegetation probably occur all along the coast, but these benches are evidently not very recent, as they lack well-defined facets toward the coast except at Livingston and near Puerto Cortez. At Livingston, Guatemala, the town is built on terraces 35 and 55 feet in height. Across the bay from Puerto Cortez, at Tulian, distinct 40- and 60-foot terraces were seen. No corals or marine shells were found on any of these terraces. Shells are common on the present beach, but coral fragments are absent.

Evidence of earlier subsidence in both Honduras and Guatemala was seen in the broad river valleys filled with alluvium in which the

streams are now cutting narrow channels, and in the terraces along the continental shelf. Coast charts show a shelf about 5 miles wide with terraces at depths of about 15 and 30 fathoms in the vicinity of Utilla Island. The antecedent stream, Rio Dulce, Guatemala, flows through a rock gorge, and the depth of the water through the gorge and directly behind the bar is 40 feet. No other stream along the coast has a rock bed at sea-level. Therefore data on subsidence are very fragmentary.

TECTONICS

Guatemala and Honduras are composed of two mountain systems (Fig. 1): the Pacific Cordillera, now little more than a belt of high plateaus covered with young volcanics, and the Caribbean Cordillera, consisting of east-west ranges. On the north the tectonic lines of Yucatan trend toward the Isle of Pines; in the center of Guatemala they trend toward a 3,000-fathom deep; on the south, in Honduras, they trend toward Jamaica. The two systems are in striking contrast; from the Atlantic, broad, structural valleys with a maximum length of 200 miles (Fig. 3) stretch almost across the Isthmus; from the Pacific, short, precipitous valleys extend to the high plateau between the volcanoes and almost disappear on the low plain near the coast.

It has been pointed out above that successively older formations appear on the Caribbean side of the Isthmus from north to south and that the Tertiary and younger volcanics are largely confined to the high plateau forming the backbone of the Isthmus. Pleistocene volcanoes are aligned on the inland edge of the Pacific plain parallel to the coast. The lack of any evidence on the Pacific side of Guatemala of valleys of such size that they would not be concealed by late Tertiary and more recent volcanics, the absence of a coastal plain showing uplift, and the remarkable alignment of the volcanoes point to a possible fracture zone on the western side of which a portion of the Pacific Cordillera has subsided. Along one of the principal lines of subsidence at the intersection of cross-fractures the volcanoes have been built.[1] Uniformly great depths in the

[1] The fracturing is similar to, but more complicated than, that in the Hawaiian Islands (S. Powers, "Tectonic Lines in the Hawaiian Islands," *Bull. Geol. Soc. Amer.*, XXVIII (1917), 501–14).

Pacific Ocean at no great distance from shore and the parallelism to the coast line of the submarine contours are not unfavorable to the theory of subsidence.

Diastrophic movements of considerable magnitude have taken place in Central America at three different periods: at or before the close of the pre-Cambrian, at the close of the Paleozoic, and during the late Miocene. A later movement may be dated as late Pliocene or Pleistocene. The Cordilleran axes were developed during the folding at the close of the Paleozoic, the folding being most intense toward the south. Miocene movements, though less intense, developed parallel Cordilleran trends of the Caribbean system and initiated the cycle of erosion in which the greater part of the dissection of the present mountains was accomplished. Vulcanism undoubtedly began in the present central portion of the Isthmus before the Miocene deformation, as the earlier volcanics are steeply folded. Pliocene and Pleistocene (?) sediments from Yucatan southward through Honduras show evidence of both vertical and tangential movements, tangential movements being especially notable in the youngest sediments of the Atlantic Coast region near Puerto Cortez and Omoa, Honduras, and Lake Izabal, Guatemala.

NOTES ON A COLLECTION OF ROCKS FROM HONDURAS, CENTRAL AMERICA

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Introduction.—The rocks described in this paper were collected by Dr. Sidney Powers during the summer of 1917 from the province of Atlantida, northwestern Honduras, and from the outlying island of Utilla. A summary of the general geology of the region is given in the paper preceding this by Doctor Powers. A high range of mountains composed of batholithic intrusions of granodiorites, the Sierra de Pija, extends along the northern border of Honduras and sends radiating spurs toward the coast. Most of the rocks were collected from stream valleys cutting the northern slopes of these mountains.

The chief centers from which collections were made are Tela, Puerto Cortez, San Pedro Sula, La Ceiba, and Nueva Armenia. These towns are shown in Fig. 2 of the preceding article. The island of Utilla lies 20 miles off the coast and is one of the Bay Islands.

Rocks from Utilla Island.—Utilla is largely fashioned from Quaternary basalts. The basalt which occurs back of the town of Utilla is gray black in color, some of it dense, some of it vesicular. In certain varieties the feldspars abound; in others augite and olivine phenocrysts are more abundant. The groundmass has an ophitic texture and is composed of andesine, augite, and olivine. The feldspar phenocrysts are zoned and have the composition of basic andesine and medium labradorite. Basalts from Stuert Hill, which is probably the center from which the flows came, are similar to the type just described, but are more vesicular and impregnated by calcite. Stuert Hill is composed principally of agglomerate.

Pumpkin Hill, $1\frac{1}{2}$ miles southwest of the town Utilla, is underlain by tuff composed of coarse bits of lapilli and angular fragments

of coral limestone set in a paste of yellowish white ash. The vesicles of basalt are filled with opal, showing that the rock has been thoroughly leached since its deposition on a tuff cone in relatively shallow water.

Rocks from the Tela district.—Near the town of Tela there are a large variety of igneous and metamorphic rocks which are more or less intimately connected by transitional facies. The igneous types vary from granodiorites to gabbros. At the western end of the native village the hills are composed of medium- to fine-grained augite diorites cut by occasional quartz veins. The diorites are composed of basic oligoclase feldspar, biotite, diallage, and accessory apatite and magnetite. Three miles west of Tela, Triunfo Point is formed by a hill of true diorite which varies greatly in size of grain within a few feet. The diorite is black and white in color and consists of acid labradorite, common hornblende (pleochroic olive green to yellow), and accessory magnetite. Similar diorites are exposed in a cut along the Tela Railroad 7 miles west of Tela, and in the headland Bishop Point, 5 miles west of Triunfo Point, the last rocky point for 70 miles to the west. South of Tela, toward the mountains which are locally called the Shark Mountains, felsodacites outcrop in Tela valley associated with dioritic gabbros. The felsodacite is dirty buff in color and contains small phenocrysts of quartz and larger phenocrysts (3 to 8 mm.) of feldspar. The microscope shows that in the recrystallized mosaic of quartz and feldspar myrmikitic intergrowths are common.

A large number of rocks were collected in the Quemada Hills on the west side of Micos Lagoon and about 12 miles east of Tela. The accompanying sketch map (Fig. 1) shows the principal points visited. Typical diorites, such as compose Triunfo Point, outcrop on Mũnos Hill. Philipe Hill is composed of a sheared granodiorite, light gray in color. Under the microscope the rock shows a mosaic texture. Quartz and orthoclase with oligoclase are the chief minerals, but minute flecks of hornblende are abundant and titanite and apatite are present. Apparently intrusive into the granodiorite, since it is less sheared, is a basic diorite composed of labradorite ($Ab_{40}An_{60}$) and a hornblende which is pleochroic, bluish green to light yellow. Apatite and pyrite are also present.

Diorites outcrop on Leandro Hill, and coarse-grained types with large hornblende crystals occur in the valley southwest of this hill. Medium-grained gabbros rich in labradorite, which gives them a greasy, brown appearance, are found on Frijole Hill.

Along Cow Creek and the adjacent creek on the west, Leandro, a series of metamorphic rocks largely derived from tonalites or diorites is found. Pegmatitic facies of the tonalite composed of quartz, orthoclase, and black tourmaline are common in the valley

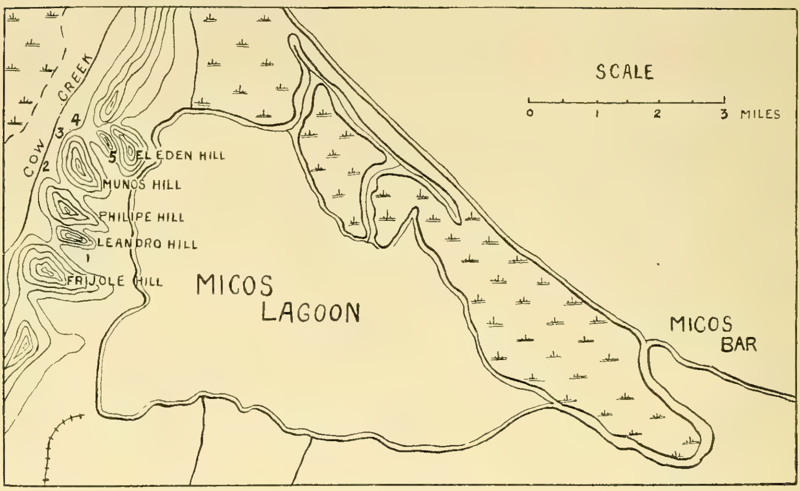

FIG. 1.—Map of vicinity of Micos Lagoon, Northwest of Tela, Honduras

near locality (1) (Fig. 1). At locality (2) a dioritic orthogneiss outcrops. The rock is dark gray in color and is composed of sheared oligoclase feldspar in parallel bands with quartz veinlets. Parallel fine needles of hornblende add to the banded effect and bend about occasional phenocrysts of feldspar. An epidote orthogneiss occurs near locality (3). It is composed of epidote, hornblende, and labradorite and is banded gray and black in color. A greasy mica schist outcrops at locality (4). The paper-thin, crenulated bands of muscovite bend about brecciated crystals of oligoclase which appear as small "augen" inclusions on the cross-fractured rock.

On El Eden Hill, locality (5), hornblendite outcrops north of a ridge of quartzite which is tilted on end. The hornblendites were

undoubtedly derived from the metamorphism of diorites. They are composed of andesine and a hornblende which is pleochroic light yellow and olive green to bluish green. Associated with the hornblendites are dioritic biotite orthogneisses.

Along the Tela Railroad 14 and 16 miles east of Tela sedimentary quartzites and gneisses are exposed, while at Uraca, 56 miles southeast of Tela by rail, medium- to coarse-grained tonalites composed of quartz, oligoclase, and a little hornblende outcrop over a large area. The tonalites extend eastward past San Pedro Sula.

Rocks from Puerto Cortez and vicinity.—The region about Puerto Cortez has been built by shoreward currents and by the vegetation in swamps. But across the bay the waves have exposed a series of Tertiary sandstones which are greenish gray when fresh, but which oxidize to a limonitic clay. They are composed of very fine grains of quartz and muscovite mingled with an equal proportion of glauconite particles. The rock is gritty and friable and hence is quite like a typical green sand both in color and texture.

Proceeding southward along the Honduras National Railroad from Puerto Cortez volcanic rocks similar to those on the island of Utilla overlie sheared felsodacites at Chameleconcito. The particular specimen collected is a dense porphyritic basalt composed of large phenocrysts of labradorite, olivine, and augite set in a cryptocrystalline groundmass of the same minerals associated with magnetite dust.

At Baracoa specimens of an even, fine-grained, dioritic gneiss were found associated with an actinolite gneiss composed entirely of actinolite in rosettes of radiating fibers. Near La Pimienta there are chocolate-colored felsites which show a flow structure and carry small phenocrysts of oligoclase feldspar. When decomposed they form a residual clay very free from iron compounds. They have not been sheared or folded like the other felsites described because they are much younger—probably post-Cretaceous.

Rocks from Landslide Valley, San Pedro Sula.—On account of residual soils fresh rocks are seldom found in Honduras. An exception to this rule occurs, however, in the valley southeast of San Pedro Sula conspicuous for the large bare face of a mountain left by a landslide. Here bronze-colored biotite schists are

associated with diorites. The schist is composed of paper-thin layers of biotite bending around augen crystals of oligoclase and is similar to the schist occurring west of Micos Lagoon, near Tela, save that the mica is predominatingly biotite instead of muscovite. The microscope reveals a granular paste of fine quartz with rosettes of muscovite and parallel plates of chestnut-brown biotite. The diorite is a medium- to coarse-grained variety whose relation to the schist is unknown. Occasionally the diorite is sheared and epidotized.

Rocks from La Ceiba and vicinity.—Among the streams extending from the coast into the hills southeast of La Ceiba, the nearest is Rio Danto. A number of river pebbles were collected from its bed and one specimen was collected from an outcrop in the stream. The pebbles came from the higher interior hills near the headwaters of the coastal streams and were largely tonalites or allied types. The residual bowlders show that the region about La Ceiba is underlain by agglomerates and flows of acid rocks which toward the east around Tela are transformed into gneisses and schists by dynamic metamorphism. A tuffaceous agglomerate containing pebbles of felsodacite is much epidotized, but the microscope shows phenocrysts of oligoclase-albite replaced in part by a mosaic groundmass of small quartz particles. A trachyandesite from the same locality, outcropping in the river, is light yellow to buff in color and shows a slight flow structure. The thin section shows phenocrysts of oligoclase-albite which are not distinct in the hand specimen. The groundmass is composed of a fine mosaic of feldspar and quartz and occasionally there are nests of feldspar in trachytic arrangement.

From the hills north of Rubber Grove, a station on Vaccaro Brothers Railroad, 5 miles southeast of La Ceiba, aporhyolites and rhyolitic agglomerates were obtained. The agglomerates are composed of red pebbles of aporhyolite and jasper bound together by a red quartzose cement.

The Congrejal River flows into the ocean past the town of La Ceiba. Along its lower course acid flow rocks are exposed, but farther south among the mountains it cuts tonalites and gran-

odiorites. Near the town a rounded hill is composed of felsodacite intruded by diorite. The diorite is a medium- to coarse-grained type consisting of hornblende and oligoclase. The hornblende is pleochroic, chestnut brown to light yellow. The oligoclase is occasionally replaced along the albite twinning planes by magnetite. Tonalite porphyries containing phenocrysts of quartz and oligoclase in a glassy groundmass are frequently exposed, as are also agglomerates containing pebbles of the porphyries.

A biotitic tonalite collected 8 miles up the Congrejal valley at an elevation of about 300 feet is pure white in color and coarsely crystalline. It consists of predominating oligoclase feldspar and quartz with occasional flakes and bunches of biotite a centimeter in diameter. A granodiorite which consists of oligoclase-albite, microcline, quartz, and hornblende was collected near the same locality. The rock has been subjected to great strain and the cracks are filled by a mass of small quartz crystals. The tonalite is seen in the field to be cut by the granodiorite, but the contact shows very little chilling of the latter rock. A dark-greenish porphyry cutting the granodiorite and a breccia composed of fragments of granodiorite in a granular matrix, but of uncertain relationship to the other rocks, are seen south of large exposures of the granodiorite in the river bed. North of these exposures, about 5 miles up the valley, quartz veins are very abundant, cutting a rock which looks like a hydromica schist, but which is probably a metamorphosed igneous rock.

Near the mouth of the Masica valley, 25 miles southeast of La Ceiba, there are found tonalites and allied rocks similar to those exposed in the Congrejal valley, but here associated with basic types. An olivine diabase was collected which is composed of labradorite, augite, olivine, biotite, a little brown hornblende, and pyrite. A coarse-grained black wehrlite was also found consisting of olivine and augite in about equal proportions and a very small amount of labradorite. The olivine crystals often include rounded and resorbed bits of augite.

At San Francisco, 15 miles southeast of La Ceiba, basalt porphyry bowlders with labradorite phenocrysts 2 to 3 cm. in

diameter were picked up in the stream bed. A granodiorite collected from this vicinity has approximately the following composition:

	Percentage		Percentage
Oligoclase	50	Biotite	4
Orthoclase	20	Hornblende	1
Quartz	25		
			100

Rocks from the vicinity of Nueva Armenia.—Hot springs in the hills 5 miles south of Nueva Armenia and $1\frac{1}{2}$ miles east of the Tropical Timber Company's railroad well up through tonalites and have kaolinized these rocks extensively. The fresh tonalite is a light-gray rock consisting of oligoclase, quartz, and hornblende. Gneissic varieties of the tonalite are found associated with coarse-grained diorites composed of oligoclase and hornblende. One specimen of the diorite shows a small amount of biotite.

Summary.—The igneous and metamorphic rocks collected from the province of Atlantida, Honduras, include the following types:

- Granular rocks
  - Granodiorite
  - Tonalite
    - Biotite tonalite
    - Pegmatite tonalite
  - Diorite
    - Augite diorite
  - Gabbro
    - Dioritic gabbro
  - Wehrlite
- Cryptocrystalline and glassy rocks
  - Aporhyolite
  - Felsite and agglomerate
  - Tonalite porphyry
  - Felsodacite and agglomerate
  - Trachyandesite
  - Olivine basalt, agglomerate, and tuff
- Metamorphic rocks
  - Dioritic orthogneiss
  - Epidote orthogneiss
  - Actinolite gneiss
  - Hornblendite
  - Biotite schist
  - Quartzite

The granular types occur largely near the summits and on the north slope of the mountains forming the Sierra de Pija, while the extrusive types are found near the coast. The geologic events in the history of the region as revealed by the rocks studied may be epitomized as follows:

1. Intrusion of granodiorites and tonalites accompanied by the extrusion of allied rock types.
2. Folding.
3. Intrusion of diabases and diorites.
4. Faulting and crushing.
5. Extrusion of olivine basalts.

LOESS-DEPOSITING WINDS IN LOUISIANA

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The data on which this paper is based were accumulated from field work on the two loess belts of Louisiana together with a few examinations of loess at Vicksburg and Natchez, Mississippi. Practically all the evidence points to an eolian origin for the southern loess. Assuming this origin, it appears from two lines of evidence, namely the amounts and thickness and the chemical composition of this loess, that the principal depositing winds were westerly and southerly.

THE LOESS

The loess in Louisiana is of brownish to gray-brown colors and shows the usual vertical cleavage. For the most part it overlies Lafayette and Columbia sandy and gravelly materials and Pleistocene clays which are usually correlated as Port Hudson. It was deposited on an eroded surface, hilly in most places where the loess overlies the Lafayette and Columbia formations, and rolling to undulating where it overlies the clays (Fig. 1). There are two loess belts fringing the Mississippi lowlands, extending nearly to the Gulf. The eastern belt, beginning about 15 miles south of Baton Rouge, about 80 miles from the Gulf, with a width of about 15 miles, widens to the northward to a width of perhaps 40 miles in Mississippi. This belt continues northward through Tennessee to the Ohio River with practically no interruptions except at stream valleys. The western belt begins near Lafayette about 40 miles from the Gulf and extends to the Red River valley, a distance of about 50 miles, with an average width of 8 to 10 miles. Ten miles to the north the loess again appears in an island-like area, the Avoyelles Prairie, of about 80 square miles. About 40 miles northeast the loess belt again reappears at Sicily Island, from which it extends northward into Arkansas in a belt known locally as the

Bayou Macon Hills, with a width varying from 5 to 15 miles. The western loess belt is seen to be somewhat longer but much narrower than the eastern belt.

These belts in Louisiana show contrasts in thickness and in the outlines of their margins away from the Mississippi. The eastern belt, beginning with a thickness of from 10 to 12 feet, thickens to

FIG. 1.—Loess overlying a buried hill of red Lafayette materials. The arrows point to the contact. West Feliciana Parish, Louisiana.

the northward to about 15 to 20 feet at Bayou Sara, 35 miles to the northward; at Vicksburg it is from 30 to 40 feet thick. The western belt, with about the same thickness at the south, thickens but little to the north, being but 12 to 15 feet thick in the Bayou Macon Hills, nearly 200 miles to the north. The eastern belt in Louisiana ends rather abruptly at the Amite River. On the west side of this stream the observed thickness is about 6 feet, while across the valley two miles to the eastward the loess is much thinner and sparsely developed. On the other hand, the western belt thins so gradually that its western limits can only rarely be observed. The

two belts correspond in having the thickest loess near the Mississippi lowlands.

Here, as in most places elsewhere, the loess shows the characteristic uniformity in size of particles. There are no available mechanical analyses of the lower part of the loess, but several analyses of lower subsoils show that about 70 per cent ranges in size from $\frac{5}{100}$ to $\frac{1}{100}$ mm. in diameter and about 20 per cent is below this diameter. The remainder is composed of particles but slightly larger than $\frac{5}{100}$ mm. in diameter. In general the loess particles of Louisiana seem to be more rounded than those farther north, so far as the writer can judge from the examination of half a dozen samples from Iowa and Illinois. This difference is doubtless to be explained by the fact that the southern loess particles have been subjected to long transportation by the Mississippi. In the main body of the loess an examination of perhaps 500 exposures shows little if any stratification, although here and there there are faint indications of such structure. For example, the snail shells which are abundant locally show in a few places a rude horizontal alignment and lie in thin dark streaks suggesting buried soils. In a few places dark bands never more than a few inches long and probably due to iron and manganese coatings suggest that these substances have accumulated along bedding planes. A sharp contact between the loess and the underlying materials has never been observed, but rather there is a transition zone 3 to 20 inches in thickness. The transition is most indefinite between the loess and underlying clays, for there is more or less similarity in texture and in some cases in color. Where Lafayette and Columbia sandy materials underlie the loess, there is in places a "feathering" of the one into the other and in places very faint stratification.

THE ORIGIN

Two problems are involved, (1) the source of the loess materials, a problem with which this paper does not deal directly, and (2) the secondary or the depositing agents. Since the loess belts follow only the Mississippi lowlands and do not extend up the tributaries, it is clear that there is a genetic relation between the river from Cairo southward and the loess. The Mississippi doubtless carried

the loess materials, and the agent of final loess placement on the uplands adjoining the river narrows either to water deposition or to winds carrying materials from the lowland.

The explanation of southern loess as wind-blown dust not only presents the fewest difficulties but is distinctly supported by most of the loess features. The smallness of grains can be explained by the weakness of wind transportation, for, according to the experiments of Udden, only dust particles with diameters of .18 mm. and less are readily borne by ordinary winds.[1] We have noted that about 70 per cent of the loess is composed of silt particles from .05 to .01 mm. in diameter and that the mechanical composition is notably uniform. The practical absence of coarse particles is, of course, explained by the inability of ordinary winds to carry them. Udden thus explains the small percentages of very fine particles.[2]

The writer suggests another reason for the relatively small percentages of very fine materials (clays) in the loess. Observations on clay and silt plowed fields in Kansas during dry seasons showed that more dust blows from the coarser silt soils than from the clay soils. The reason apparently is that, during a dry season, the clays bake more than the silts and so offer more resistance to the winds. According to this conclusion, if the Mississippi upon subsiding left areas covered here with silt and there with clay, the winds would carry a larger proportion of silt than of clay.

In a large river like the Mississippi it would seem impossible for the water to deposit its sediment with practically no stratification, even if the water carried only loessial materials, for the loess contains from 5 to 10 per cent of fine sand, and in places this coarser material would be segregated. The loess materials carried by the Mississippi were in large part carried from drift regions to the northward and, even granted that the drift furnished only fine materials, the streams south of the glaciated region, such as the Arkansas, Yazoo, and Red rivers, were doubtless contributing their sandy loads, so that the Mississippi could not have carried only a loessial

[1] *Journal of Geology*, II (1894), 323.

[2] "The finest materials carried by the air are not deposited in so great a proportion with the coarse materials as they would be if the atmosphere carried a greater load. The finest materials settle only in extreme calms" (*ibid.*).

load to the Louisiana region. Furthermore, such a river in flood would necessarily back up the tributaries and loessial materials would be deposited along the tributaries in contrast with the actual fairly straight margin where it crosses a tributary.

So far as the structure of the loess is concerned, it might have accumulated in lakes or have been deposited by winds, but in the hundreds of miles of loess belts below Cairo there are no restraining barriers which would impound lakes. Moreover, lakes in which 10 to 50 feet of loess accumulated must have existed long enough for deltas to have been built and shore lines developed, for in such temporary lakes as the Red River raft lakes of Louisiana one may find well-developed shore lines around these nearly drained lakes. No such shore lines have been seen in the Louisiana loess areas and none to the writer's knowledge have been reported elsewhere in the Lower Mississippi Basin.

The relations of the loess to the underlying buried Lafayette-Columbia sandy hills near the Mississippi strongly suggest an eolian origin (Fig. 1). The absence of truncation of these buried hilltops, the very faint or frequent absence of interstratification of loess and sand at the contact, all point to a weak depositing agent such as wind. The greater thickness of loess near the Mississippi is not inconsistent with an eolian origin, for the dust-laden winds blowing from the lowlands to the uplands would have their velocity checked and so drop part of their load near the river. The work of Shimek shows that the loess fossils in this region, mostly snails, belong to a land fauna, there being "no species which are aquatic or even semi-aquatic,"[1] and the virtual absence of a water fauna is equally significant.

DIRECTIONS OF LOESS-BEARING WINDS

Assuming the eolian theory of loess in Louisiana, there are three lines of evidence available as to the directions of loess-depositing winds, namely: (1) the width and thickness of the loess belts on either side of the Mississippi, (2) the composition of the loess, and (3) the thickness of loess on some isolated areas which were exposed to the sweep of winds from many directions.

[1] *Am. Geologist*, XXX, 282.

1. The greater thickness and width of the eastern loess belt have been noted by many observers and usually explained as due to stronger and perhaps more persistent westerly depositing winds. From a rough calculation based on field notes the writer estimates that the loess in Louisiana below the Mississippi state line includes about 4 cubic miles, while the corresponding portions of the western belt includes only .8 of a cubic mile, or, roughly estimating, there is about five times as much loess in the lower eastern belt as in the corresponding portions of the lower western belt. These contrasts point to the greater work of westerly as compared with easterly winds.

2. The same conclusion seems to be indicated by the composition of loessial soils in the two belts. While the analyses are of soils and subsoils only, it is believed that the *range* of their compositions corresponds to that of the underlying loess, since the soils have been subjected to practically the same weathering processes over both belts. Taking the composite soil analyses of the eastern loess belt below the Mississippi state line and the corresponding portions of the western belt, we have the following data:[1]

	Number of Analyses	Lime (Lbs. per Acre)	Potash (Lbs. per Acre)	Phosphoric Acid (Lbs. per Acre)
Eastern belt	21	5,540	8,500	980
Western belt	14	6,000	8,920	1,800

The lime and potash are slightly higher in the western belt, and the phosphoric acid decidedly so. So far as can be determined by a microscopic examination, the lime and potash occur in feldspars with diameters mostly $\frac{1}{100}$ mm. in diameter or less. Most of the phosphoric acid occurs in the very fine particles, the fine silts and clays, with diameters below $\frac{5}{1000}$ mm. These fine particles are difficult to study microscopically, and the writer has been unable to identify the phosphate-carrying minerals except for an occasional particle of apatite. However, the point to be emphasized in this connection is that the particles carrying lime, potash, and phosphoric acid are very small, and it is believed that the higher

[1] Analyses by I. Selecter, Soil Chemist, Louisiana State Agricultural Experiment Station.

percentages of these minerals in the western belt are due to a differential selection of wind load. The weaker easterly winds carried a relatively finer load than the stronger westerly winds, with the result that higher percentages of lime, potash, and phosphoric-acid-carrying minerals were deposited in the western loess belt.

3. The third line of evidence concerns the effectiveness of northerly winds as compared with southerly winds as loess-carrying agents. The Avoyelles Prairie (see Fig. 2) is an island-like area of

FIG. 2.—Map showing the loess belts (dotted) in Louisiana and Mississippi. (Loess in Mississippi after Mississippi Geological Survey.)

about 80 square miles, which is entirely surrounded by alluvium and capped by a layer of loess overlying Lafayette-Columbia and Port Hudson materials. The platform on which the loess rests is 10 to 15 feet above the alluvium in the two places where the top of the platform was observed. This relatively elevated area was exposed to the sweep of the winds from all directions, with no loessial soil within 10 to 30 miles, and it seems clear that the prevalent winds would deposit the thickest loess in a manner analogous to the drifting of snow in some regions. The loess-bearing winds from the south, for instance, would drop a portion of their load on

reaching the low elevation. If the elevation were of small area, there might also be an accumulation of dust on the lee side of the obstruction, as snow drifts on the lee side of a tight fence; but in this case the winds passed over several miles of low upland, and it seems probable that most of the heavy load would be deposited on the windward side and but little dust would be left to accumulate on the leeward side. The loess on the Avoyelles Prairie is about 12 feet thick at the southern end of the area and 6 to 7 feet thick at the northern end, a difference in thickness indicating southerly rather than northerly winds as the main depositing agents. No sections were observed which allow comparisons of thickness on the eastern and the western sides. About 40 miles east of north from the Avoyelles Prairie is Sicily Island, the southern extremity of the Bayou Macon Hills, which, as we have seen, is a loess-covered ridge extending from Arkansas into Louisiana. At the southern end of Sicily Island the loess is from 12 to 14 feet thick, and about 7 miles northward it thins to 7 to 10 feet. The evidence here is not so clear, for the dust may have accumulated on the lee side of the ridge from northerly winds, or it may have accumulated from the deposition by southerly winds at the southern side of Sicily Island. However, it seems that the thicker loess at the southern ends of both these elevations points to the greater effectiveness of southerly winds as loess-depositing agents as compared with northerly winds.

PRESENT WINDS

There is some interest in comparing modern wind directions to ascertain, if possible, whether the most effective modern winds in this region are at present westerly and southerly. Unfortunately no positive conclusions can be reached, because one cannot be sure that the average for so short a time as that for which we have records represents the modern wind directions, and, furthermore, the important elements of wind persistence and velocity are not given in the reports. Fig. 3 shows the average prevailing wind directions for the several months at New Orleans, Louisiana; Vicksburg, Mississippi; and Memphis, Tennessee, for periods of thirty-six, thirty-five, and thirty-five years respectively. The winds at Vicksburg and Memphis are more significant than those at New

Orleans, for Vicksburg and Memphis are located on the loess, and, moreover, the directions at New Orleans are complicated by local land and sea breezes which do not extend far inland. It will be seen that the prevailing winds at New Orleans and Vicksburg are

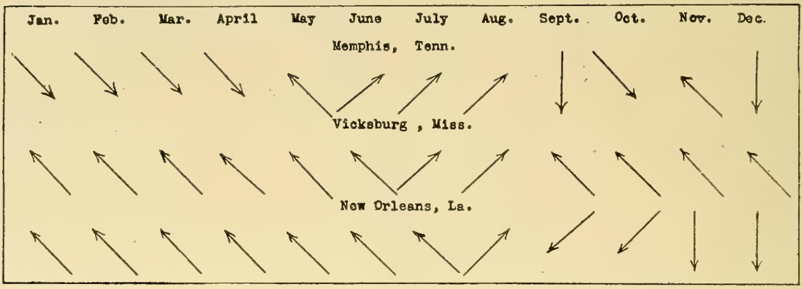

FIG. 3.—Diagram showing the directions of prevailing winds at New Orleans, Louisiana, Vicksburg, Mississippi, and Memphis, Tennessee. (Data from *Bulletin Q*, by A. J. Henry, U.S. Weather Bureau, 1906.)

southerly, and probably would account for the greater accumulation of loess at the southern ends of Avoyelles Prairie and Sicily Island. On the other hand the easterly winds greatly exceed those from westerly directions, except at Memphis, where the westerly

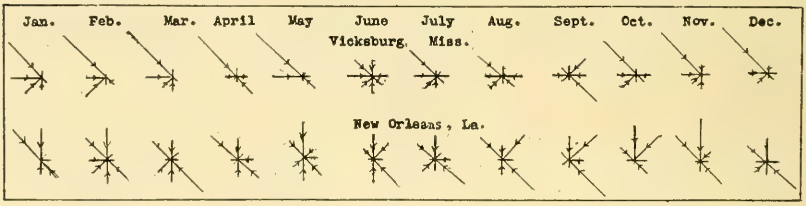

FIG. 4.—Diagram showing the occurrences of high winds at New Orleans, Louisiana, and Vicksburg, Mississippi. Lengths of arrows are proportional to frequency. (After data by I. M. Cline, of the U.S. Weather Bureau at New Orleans, and W. E. Barron, of the U.S. Weather Bureau at Vicksburg.)

winds predominate. Fig. 4 shows the frequency of high winds at New Orleans and Vicksburg. At New Orleans about 26 per cent of high winds are from easterly directions, 17 per cent from westerly directions, 32 per cent from northerly directions, and 25 per cent from southerly directions. At Vicksburg 29 per cent of high winds

are from northerly directions, 16 per cent from southerly directions, 11 per cent from easterly directions, and 43 per cent from westerly directions. It should be noted that only the highest winds are included in the data given above. Undoubtedly the high winds are effective dust carriers, but loess is so fine grained that it could doubtless be carried by ordinary winds, other things being favorable. Fig. 3, which shows the winds of all velocities, probably is more significant than Fig. 4, which shows only a part of the high winds. Remembering the much greater thickness and width of the eastern loess belt, it would seem that the present winds would not be competent to account for the disparity between the eastern and western loess belts. This is certainly true so far as occurrences are concerned, and there is no reason to believe that either the persistence or velocity of winds from any one direction are especially notable. During loess-depositing times westerly winds must have been more predominant than at present. The present southerly winds would seem to be competent to deposit the greater thickness of loess at Avoyelles Prairie and Sicily Island. Obviously more observations of loess thickness on isolated areas are needed before positive conclusions can be drawn as to the efficiency of southerly winds.

SUMMARY

(1) The greater efficiency of westerly winds in the southern loess belts is shown by (*a*) the greater width and thickness of the eastern loess belt and (*b*) by the higher percentages of lime, potash, and phosphoric acid of the soils of the western belt. (2) The greater thickness of loess on the southern sides of two isolated loess areas indicates that southerly winds were more efficient in this region than northerly winds. (3) From the meager data available it would seem that westerly winds were more frequent and effectual in loess-depositing times than at present.

VOLUME CHANGES IN METAMORPHISM

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Introduction.—It is the purpose of this paper to consider volume changes of rocks in relation to metamorphism. This is a subject which has already received much attention by geologists and physical chemists, but it seems to me that the former have not always appreciated the true conditions of metasomatism, while the latter have limited themselves largely to the consideration of transformations in systems in open space. The changes in the rigid rocks are subject to certain limitations to which I believe sufficient attention has not been directed.

Known changes of volume.—It is evident and well known that volume changes in rocks take place. The most efficient agencies are molecular forces: heating and cooling, fusion and solidification, molecular rearrangement (as when a mineral passes any inversion point). All of these may affect the volume of large or small masses of rocks. Injection of igneous material may increase the volume. Stretching of a geological body may result in cracks and fissures, increasing the bulk volume, and if these are filled by circulating solutions the actual volume will be greater than before. In the same way processes of filling may increase the actual volume of a porous rock. It is also well known that diminution of volume may take place in unconsolidated sediments under pressure, by closing of pores or other openings, and by incidental squeezing out of any fluid or gaseous phase which the rock may contain. In such rocks lateral movements of plastic material may occur, though this would only effect a relative change of volume. Similar relative volume changes occur by recrystallization under conditions of rock flowage (as in case of marble or ice).

Close to the surface where disintegrating agencies are at work volume changes may take place. The pressure is slight and chem-

ical reactions proceed accompanied by increase or decrease of volume. Here hydration will result in expansion and strong solvent action may be followed by contraction of volume.

Metamorphism and metasomatism.—Metamorphism is here defined as the sum total of the chemical and mechanical changes which take place in solid rocks, below the zone of oxidation. The agents are heat, pressure, and chemical energy. Metamorphism by pressure is probably always accompanied by some chemical change. Chemical energy works by means of solutions, gaseous or liquid, which penetrate the rocks on capillary and supercapillary openings.

Metasomatism is here defined broadly as any change in composition of a mineral when exposed to conditions under which it is unstable. Solutions, gaseous or liquid, effect the change. A more restricted definition is that metasomatism comprises any change in composition of a mineral in a solid rock induced by a change in the physical conditions and resulting in its space being occupied by another mineral stable under the prevailing conditions.

Metamorphism is in most cases accompanied by metasomatism of individual minerals and usually also by metasomatism of the rock as a whole, though the latter change may proceed very slowly. If the supply of new material is rapid the composition of the rock may be greatly changed within a short time. Replacement is used as equivalent to metasomatism.

Thesis of this paper.—In a previous paper,[1] principally devoted to metasomatism in mineral deposits, I have advanced the view that replacement normally occurs without change of volume of individual minerals or rocks. I would now like to broaden this theory by the thesis that metamorphism by replacement does not normally involve changes of volume.

Replacement.—Replacement in solid rocks consists in solution of the host mineral, followed immediately by deposition of an equal volume of the guest mineral. This is an empirical observation based on the microscopic examination of rocks. In other words the volume of the replacing mineral equals the volume of the mineral replaced. Deposition follows so closely upon solution that at no

[1] "The Nature of Replacement," *Econ. Geology*, VII (1912), 521–35.

time can any open spaces be discerned under the microscope. It is evident, however, that capillary spaces are necessary for the movement of the fluid phases which in most cases are aqueous solutions. In fact, replacement usually begins from such capillary cracks or from a series of minute fluid inclusions along such a fissure. Replacement is primarily caused by solution or decomposition of the host mineral in solute films separating grains and filling capillary fissures. The solution of the host mineral produces supersaturation in the liquid, and an amount of secondary material is precipitated equal to the volume of the host mineral removed.

Replacement proceeds particle by particle but not "molecule for molecule." In other words there is no simple molecular equivalence between the material dissolved and the material precipitated. Replacement proceeds independently of specific gravity and molecular volume. Chemical reactions may take place in the contact film, but the sum total of the change is not expressible by the chemical formulas usually supposed to represent the process.

In some cases there is simply solution and deposition without chemical reaction, as when pyrite replaces calcite or limestone or shale, but whether or not the exchange is accompanied by chemical reaction does not influence the law of equal volumes. Replacement is dependent upon the velocity of the solution movement and naturally also upon composition, pressure, and temperature of the replacing solution. If the speed and chemical activity of the solutions be great the empirical volume law may fail to hold, deposition will lag behind solution, and a drusy texture will result. This happens occasionally in some metasomatic processes in the formation of mineral deposits, but in metamorphism of rocks the solutions move slowly and only a small amount of new material is introduced, so that the resulting textures are always compact. Even in the case of drusy texture the bulk volume remains the same and subsequent rock pressure fails to close the cavities, even under the weight of a rock column of 10,000 to 15,000 feet. Ultimately, at extreme depths these cavities would most probably be closed with permanent reduction of volume if they have not previously been filled by cementing solutions.

While, therefore, in extreme cases of metasomatism there may be diminution of actual volume expressed in porosity, the opposite, i.e., increase in volume, it is believed, will not take place by replacement in rigid rocks.

Form and texture of guest mineral.—The guest mineral may form aggregates with their irregular outlines simply determined by the ways open for the replacing solutions. In this case, as in replacement of feldspar by sericite, there are capillary openings between the individuals of sericite, and the space is thus filled less continuously than in the host mineral. In other words the porosity may increase by several per cent. The altered rock is then more accessible to later solutions and may easily suffer further alteration if the solutions change so as to make the new mineral unstable.

In other cases the guest mineral is compact and may assume its own crystal form, owing, it is believed, to differential pressure and corresponding difference in rapidity of growth in certain directions. At times the replacement may proceed so rapidly that parts of the host mineral or host minerals become inclosed by the guest mineral, as frequently seen in quartz crystals in limestone or garnets and ottrelites in crystalline schists.

Movement of solutions on capillary fissures.—I am aware that attempts have been made to show that circulation of solutions on capillary fissures is so slow as to be negligible.[1] While not able to refute these calculations, I can only say that the whole process of metamorphism appears to be opposed to such a conclusion.

Metasomatic shells.—It is frequently observed that metasomatic crystals, for instance, cubes of pyrite in feldspar, are surrounded by a thin covering of another mineral, i.e., quartz or chlorite following the outlines of the crystal. This is believed to mean that at a certain stage the iron solutions failed. The replacement proceeded, but instead of pyrite the next combinations available in the replacing solutions were precipitated.

Complex replacement.—One guest mineral may replace two or several host minerals without change of its crystallographic form. One pyrite crystal may extend across the contact of a quartz and a

[1] J. Johnston and L. A. Adams, *Centralblatt für Mineralogie*, 1914, p. 171.

feldspar grain. In schists one garnet crystal may replace hundreds of small individuals of biotite, quartz, and feldspar.

Examples of replacement.—The following instances are mentioned, in order to express more precisely what processes are believed to be active in certain cases.

In the simple case when pyrite replaces calcite the solutions need to carry iron sulphide, alkaline sulphides, and carbon dioxide. As each particle of calcite is dissolved as bicarbonate, the solution becomes supersaturated for FeS_2 and an equal volume of this compound is precipitated.

In the more complicated case of replacement of orthoclase by pyrite the entering solution would have the same composition as indicated above. As each particle of orthoclase is decomposed into potassium carbonate, colloid silica, and colloid aluminum silicate, all of which are carried away, a corresponding volume of FeS_2 is deposited.

When pyrite replaces chlorite the entering solution may contain only hydrogen sulphide, iron carbonate, and carbon dioxide. As each particle of chlorite is decomposed into magnesium bicarbonate, ferrous bicarbonate, colloid silica, and colloid aluminum silicate, a reaction takes place between the ferrous carbonate and the hydrogen sulphide, resulting in the precipitation of an equal volume of iron sulphide. The guest mineral contains much more iron than the host mineral and the additional amount needed must be supplied by the entering solution.

Every petrographer knows how frequently soda-lime feldspar or anorthite is replaced by calcite. It is usually explained as a simple case of the lime in the feldspar combining with carbon dioxide. A calculation based on respective specific gravities of 2.75 and 2.71 will show that one cubic centimeter of anorthite yields 2.20 grams alumina and silica, which must be carried away. In order that the resulting calcite may fill the space made vacant by the anorthite the solutions must supply an additional amount of 0.97 grams CaO besides the necessary CO_2, considering that one cubic centimeter of calcite contains 1.52 grams CaO and 1.19 grams CO_2.

The conversion of olivine (forsterite) to iron-free serpentine is usually expressed by the formula:

$$2Mg_2SiO_4+2H_2O+CO_2=H_4\,Mg_3Si_2O_9+MgCO_3.$$

Replacement by equal volumes demands that one cubic centimeter of forsterite (Sp.G. 3.21) must be decomposed and its space filled by serpentine (Sp.G. 2.50). The former measure contains 1.83 grams MgO and 1.38 grams SiO_2, while one cubic centimeter of pure serpentine contains 1.08 grams MgO, 1.10 grams SiO_2, and 0.33 grams H_2O. It is therefore necessary that 0.33 grams water should be added and that 0.75 grams MgO and 0.28 grams SiO_2 should be carried away. This indicates that the foregoing formula does not express the process correctly.

The well-known alteration of orthoclase to sericite is usually considered to be governed by one of the following formulas:

$$3KAlSi_3O_8+H_2O+CO_2=K\,HAl_3Si_3O_{12}+K_2CO_3+6SiO_2$$
$$3KAl\,Si_3O_8+H_2O=KHAl_3Si_3O_{12}+K_2SiO_3+5SiO_2$$

One cubic centimeter of orthoclase (Sp.G. 2.60) contains 1.68 grams SiO_2, 0.48 grams Al_2O_3, and 0.44 grams K_2O. One cubic centimeter of sericite holds 1.25 grams SiO_2, 1.06 grams Al_2O_3, 0.33 grams K_2O, and 0.12 grams H_2O. The replacement by equal volume, therefore, demands removal in solution of 0.43 grams SiO_2 and 0.11 grams K_2O, but also an addition of 0.58 grams Al_2O_3 and 0.12 grams H_2O. This indicates that the formulas cited above are certainly incorrect. The exact formula expressive of what has happened is probably very complicated. A crude approximation would be represented by the following equation:

$$3(K_2O\cdot Al_2O_3\cdot 6\,SiO_2)+4H_2O+3\,Al_2O_3+CO_2$$
$$=2(2\,H_2O\cdot K_2O\cdot 3\,Al_2O_3\cdot 6\,SiO_2)+6\,SiO_2+K_2CO_3$$

It is thus seen that sericitization involves a great addition of alumina. From where is this derived? It must be remembered that sericitization is usually accompanied by many other metasomatic processes involving replacement of aluminous silicates by pyrite, calcite, and chlorite. All these processes involve the liberation of much alumina which is ready to enter into the sericite

molecule. The last example also shows that alumina is by no means an immobile constituent during the metamorphic processes.

Preservation of texture and structure.—The best proof that no volume change takes place during metamorphism is furnished by the frequent preservation of texture and structure. We find the sharp outlines of an olivine crystal preserved, though it may be wholly converted into serpentine. We find calcareous oölites metasomatized by fine-grained quartz; silicified dolomites similarly preserve the outlines of their individual crystals. Fossils are preserved in exact outlines after silicification or pyritization. Basic rocks are chloritized with perfect preservation of outlines of ferromagnesian silicates. Zinc carbonate sometimes reproduces faithfully the texture and structure of limestone.

Replacement under uniform pressure.—It will be necessary to consider replacement under uniform pressure separately from the more complicated conditions of stress. Uniform pressure results in increase of solubility, but the effects are slight compared to a relatively small change in temperature.[1] Uniform pressure obtains in static metamorphism, which, for instance, is active in the upper part of the crust, where hydration is an important process and the temperature not high. Rocks penetrated by solutions under static metamorphism develop many minerals by replacement, for instance, sericite, chlorite, calcite, epidote, serpentine, pyrite, etc. In many cases there would be a tendency toward increase of volume because heavier minerals are replaced by hydrated products. It is believed, however, that the law of equal volumes holds strictly in case of this form of metamorphism and that changes of volume have been more frequently assumed to exist than actually proved. Consider an ordinary diabase altered to greenstone. Such a rock is a veritable laboratory of metasomatism: sericite after feldspar, chlorite after augite, epidote, calcite, and quartz after any of the primary minerals. All these replacements are constantly going on in such a rock, and I think that in no case has any change of volume been actually proved. It would not seem impossible to do so, for instance, in case of a thick dike in sedimentary rocks.

[1] J. Johnston and Paul Niggli, "The General Principles Underlying Metamorphic Processes," *Jour. Geol.*, XXI (1913), 504.

The serpentinization of magnesian rocks is often cited as a clear case of expansion by replacement. Recalling the olivine crystals referred to above, I believe it improbable that such an expansion has taken place. Large serpentine masses do not usually show the smooth slickensides supposed to be caused by this movement but are rather compact and solid, the slickensided fragments being confined to crushed zones or near the surface where yielding was possible. It seems much more probable that the replacement has been effected with extensive removal of magnesia, and this is supported by the prevalence of ascending magnesian waters where serpentines abound as in California.

Expansion by hydration of anhydrite I regard in the same light. If it takes place it is under exceptional conditions of light load. Many anhydrites altering to gypsum show no evidence of expansion, the veins of the latter mineral cross-cutting the crystalline structures without disturbance. Some gypsum evidently goes into solution.

Calculation of volume changes.—In view of what has been said above it must be concluded that the application of Lepsius' volume law[1] $\left(\text{Mol. vol.} = \frac{\text{mol. weight}}{\text{Sp.G.}}\right)$ to calculate volume changes in metamorphic rocks formed under uniform pressure is unwarranted and leads to totally erroneous conclusions, unless every detail of the complicated processes is known.

Contact metamorphism under uniform pressure.—In many cases contact metamorphism proceeds under uniform rock pressure. There is, however, strong gas pressure, and if its gradient is high this may appreciably affect the replacement. Contact metamorphism may take place with or without rock metasomatism. In the special case of intense metasomatism of limestone under the influence of extremely hot and concentrated gases one would think that changes of volume would occur if anywhere. And yet the field evidence as well as the microscopical evidence is strongly opposed to such a view as I have shown in the Clifton-Morenci

[1] Van Hise expresses this law as follows: "The volume of the original compound is to the volume of the compound produced directly as their molecular weights and indirectly as their specific gravities" (*U.S. Geol. Survey, Monograph 47*, p. 209).

district; other observers have come to the same conclusion.[1] A great quantity of CaO and CO_2 are carried away, but the volume of the mass remains the same; even drusy textures are rare. Accessions from the magma to form the contact metamorphic silicates have evidently balanced any shrinkage. If there were no accessions from the outside and if the silica and alumina combined with the lime to contact metamorphic silicates, considerable shrinkage would undoubtedly result provided always that opportunity were available for the gas phase to escape. In such a case the volume changes could be calculated by means of the appropriate simple chemical equations and Lepsius' volume law.[2] As a matter of fact such rocks do not show evidence of shrinkage, such as would be afforded by drusy texture, and no field evidence indicating such contraction has been brought forward. I must conclude that here, too, calculations of volume relations on the basis of Lepsius' law applied to the ordinarily used equations are worthless as indicating the actual process. It is believed that eventual tendency to contraction is equalized by additions of substance from circulating waters at the time of metamorphism.

In the case of hornfels derived by contact metamorphism from shales the mineralogical relations have been fully covered by V. M. Goldschmidt and earlier writers, but neither the microscope nor the field examination corroborate an assumption of reduction of volume. As heavy aluminum silicates have been formed it seems that contraction would take place unless counterbalanced by additions. Here also I believe that the replacing solutions, not necessarily of magmatic origin, have carried a certain amount of material into the rock and that when a heavy silicate is formed the remainder of the space will be filled by some other substance, say quartz or feldspar.

Replacement without liquid solutions.—Water solutions certainly circulate in the rocks of the upper metamorphic zones. It would

[1] W. Lindgren, *U.S. Geol. Survey, Prof. Paper 43*, 1905; F. C. Calkins, *ibid., Prof. Paper 78*, 1913, p. 132; B. S. Butler, *ibid., Prof. Paper 80*, 1913, p. 90; J. B. Umpleby, *ibid., Prof. Paper 97*, 1917, p. 71.

[2] Joseph Barrell, *U.S. Geol. Survey, Prof. Paper 57*, 1907, p. 149; also "The Physical Effects of Contact Metamorphism," *Am. Jour. Sci.*, Fourth Series, XIII (1902), 279–96.

be very difficult to account for metasomatism without them. It is considered possible, however, by some investigators that replacement may be effected by gaseous phases, not of magmatic origin, but simply induced by the heat of contact metamorphism in the outer zone. Goldschmidt[1] thinks so. It seems to me, however, that if this be true there would certainly be contraction evidenced in texture and possible to detect by field or microscopic methods.

Metamorphism under stress.—Under unequal pressure, as pointed out by Johnston and Niggli,[2] the solubility will be greatly increased, and its influence on reactions which are accompanied by the evolution of a gas is enormous. "Unequal stress will cause reactions between solids accompanied by the development of a gas phase to proceed to an extent which would be inappreciable in the absence of stress." The conditions in a rock under heavy stress are greatly complicated by the lateral movement of material by flowage (as shown by experiments on marble, ice, etc.). This action has nothing to do with replacement, but it certainly has a tendency to compress and thin the beds. No actual contraction of volume except by the closing of pores is involved in this operation.

Under heavy stress it is commonly assumed that all capillary spaces will be closed and that circulation of water and escape of volatile phases take place with the utmost difficulty. Whether this assumption is correct is not known. It is probably not true in case of limestone, which seems to be easily penetrated by liquids and gases.

Under and after conditions of stress there is often a strong tendency to development, by replacement, of heavy aluminum silicates of small molecular volume, such as staurolite, andalusite, and cyanite. This has generally been interpreted as meaning a reduction in volume, an interpretation which at first glance seems reasonable enough. Most calculations of changes of volume according to Lepsius' volume law are based on such changes.

[1] "The relations [referring to hornfels, etc.] are valid independently of the state of the solvents, whether these are watery solutions or a melt or whether the minerals simply are separated by a space containing their gaseous phases" (*Die Kontactmetamorphose im Kristianiagebiet*, 1911, p. 122).

[2] *Op. cit.*, p. 614.

Niggli, for instance, calculates the contractions of volume of certain ottrelite schists[1] on this basis starting with a shale of assumed composition. The conditions here are very complex, and I am sure that such computations should be undertaken with the greatest caution.

Field geology has never, as far as I am aware, proved that a contraction of volume has taken place except by rock flowage. From the standpoint of microscopic investigations there is no evidence that replacement operates in a manner different from that in rocks under uniform pressure, except that under stress the crystals tend to become elongated in direction of minimum stress. In the phenomena following relaxation of pressure, such as the development of metacrysts of garnet and andalusite, chiastolite and sillimanite, we see all the familiar phases of normal replacement, i.e., crystal form, inclusions of matrix, and complete filling of space. No crystalline schist has a drusy texture or structure indicating contraction cracks. These metacrysts or porphyroblasts develop normally across the matrix[2] and present no indication that the "force of crystallization" has bulged the rock mass, a most improbable hypothesis considering the conditions in the deep zones. Only if we assume that the rocks be actually soft is any such view tenable. It is true that the lamellae of mica sometimes bend around the crystal. These phenomena have been studied by several authors[3] who have concluded that they are caused by later mylonitic movements on gliding planes producing rotation and also development of "quartz tails" on both sides of the crystal. That rotational movements actually have occurred has been proved among others by F. H. Lahee and H. Backlund. Conditions of stress resumed after the compact crystals had been formed by replacement would naturally tend to bend the elastic mica plates around the hard bodies just as glacial clays often form layers conforming to the outline of included bowlders.

[1] *Beiträge zur geol. Karte d. Schweitz*, N.F., XXXVI, 1912.

[2] H. Rosenbusch, *Elemente der Gesteinslehre*, 1901, Figs. 73 and 74; C. K. Leith and W. J. Mead, *Metamorphic Geology*, 1915, Fig. 10.

[3] Paul Niggli, *Beiträge zur geol. Karte d. Schweitz*, N.F., XXXVI 1912; F. H. Lahee, "Crystalloblastic Order," etc., *Jour. Geol.* (1914), 500–515; H. Backlund, *Geol. För. För. Stockholm*, XL (1918), 101–203.

As the matrix is usually made up of alternating lamellae of mica and quartz it is possible that the quartz is dissolved in the direction of stress and deposited perpendicularly to it, while the mica is stable under prevailing conditions. This explanation might apply to some cases where the garnets have the appearance of having grown by forcing the schist apart. Anyway, such an action would involve an increase in volume while certainly the whole tendency in crystalline schists is more toward compression than expansion. The microscopic evidence, therefore, favors the view that replacement in crystalline schists has taken place by equal volumes, though the possibility cannot be denied that under heaviest stress the mode of replacement may be so altered that a smaller volume results.

The occurrence in many of these rocks of abundant crystals of heavy aluminum silicates raises the question whence came this concentration. The alumina could not have been derived only from the replaced host minerals; it must have been concentrated from material some distance away. It seems then that it would be necessary to assume the presence of moving liquid or gaseous solutions. And if moving solutions are admitted there is no essential difference between replacement in this case and in that of static metamorphism. These solutions would have carried other material from the outside, and the difference in volume between the newly formed heavy minerals and the dissolved host minerals would be equalized by new deposits whereby the demand for replacement by equal volume could be satisfied.

It would seem then that the conception of metamorphism under stress here outlined involves somewhat free circulation and limited addition and subtraction of material, with strong tendency toward the preservation of volume.

This is to some degree in opposition to the views of Rosenbusch and Grubenmann but in line with a recent paper by Leith and Mead,[1] in which the convergence to mineral type in dynamic metamorphism is emphasized. Duparc and others have shown us that the conversion of hornblende to uralite is not a simple paramorphism but a metasomatic process. Leith and Mead point out that the

[1] C. K. Leith and W. J. Mead, "Metamorphic Studies," *Jour. Geol.*, XXIII (1915), 600–607.

composition of a schist tends to approach the distinctive chemical characteristics of the dominant platy or columnar mineral, be it muscovite, chlorite, or amphibole. This is clearly the result of a slow metasomatic action, though this view is not definitely expressed by the authors, and if true indicates that gradual exchange of material cannot be excluded for the crystalline schists.

It is well to recognize that recrystallization in rocks under stress remains a subject beset with many difficulties and uncertainties. Fully conscious of this I advance the foregoing suggestions simply as a tentative effort from the viewpoint of a student of metasomatic action.

DESCRIPTIONS OF SOME NEW SPECIES OF DEVONIAN FOSSILS

CLINTON R. STAUFFER
University of Minnesota

A study of materials recently collected from the Detroit River series of Michigan and from the Onondaga limestone of Ontario has revealed numerous forms that cannot be identified with known species. Some of these are too fragmentary to be worthy of description, although the genera are easily determined.

The most fruitful source of this material is the Amherstburg beds in the Stony Island Dry Cut. Here great heaps of the rock removed from this part of the river bed are piled high and are rapidly disintegrating under the weathering processes. In 1916 many of the specimens found were thus badly spoiled and each year is continuing the process to ultimate destruction. Grabau and Shimer[1] have described many of these forms, but there still remain a number of fragments that should be found in well enough preserved specimens for description. Attention has been called to some of the more common genera,[2] some of the species of which are described as follows:

Arachnocrinus ignotus n.sp.[3]

PLATE I, FIG. 1

This is a medium to small sized species of Arachnocrinus. The calyx is too poorly preserved for description, or is too deeply imbedded in the matrix to be seen, but doubtless it is small.

Arms more or less uniform in size, uniserial, long, and showing frequent bifurcations. These bifurcations are not uniformly spaced on the different arms and one arm does not branch within

[1] *Mich. Geol. and Biol. Survey*, Pub. 2, Geol. Ser. 1, 1909 (1910), pp. 87–210.

[2] *Bull. Geol. Soc. Am.*, XXVII (1916), 73.

[3] To Dr. Stuart Weller is due the credit for the identification of the genus to which this specimen belongs.

the limits of the preserved specimen. It probably bifurcates farther out from the calyx. The cross-section of the arms is circular and the shape of the arm plates resembles a truncated cone with the base upward. It is not quite clear whether the number of arms is five or six because the branching in one or two cases begins so near the calyx. Dorsal canal extending throughout the arms.

Horizon and locality.—Onondaga limestone, north shore of Lake Erie, three and one-half miles east of Port Dover, Ontario.

Poterioceras canadensis n.sp.

Plate I, Figs. 2–5

Shell small, tapering both ways from the base of the chamber of habitation or last air chamber, and extending to a rather blunt point at the apex. Ventral side strongly curved, dorsal side nearly straight but curving slightly upward near the apex. Transverse section subcircular.

Chamber of habitation relatively large, being about two-fifths of the length of the shell, and more or less pear-shaped.

Air chambers regular, increasing slightly in thickness from the apex to the chamber of habitation. Septa smooth, thin, and concavity rather slight. Suture straight and horizontal.

Siphuncle small and marginal on the ventral side.

Aperture subtriangular. Hyponomic sinus well developed.

Surface of shell nearly smooth, marked only by fine lines of growth.

Horizon and locality.—Onondaga limestone. Hamilton's Quarry, Gorrie, Ontario.

Rhipidomella intermedia n.sp.

Plate II, Figs. 1 and 2

Shell subcircular and more or less lenticular in transverse section. Hinge line equal to slightly more than half the width of the shell. Both valves are convex. The pedicle valve with a flattened area along the median line just in front of the middle and extending to the front margin, where it becomes a broad indistinct sinus. Over the corresponding surface of the brachial valve there is a broad convexity.

Cardinal area probably narrow and small. The cardinal process protruding into the pedicle foramen. Teeth large and conspicuous. The specimen found is an internal mold, but it shows that the surface of the shell was covered by numerous radiating striae which were crossed by concentric growth lines.

The interior shows a strongly impressed muscular impression on the pedicle valve. This resembles very closely the similar impression in *R. vanuxemi* but differs from it in the conspicuous divisions characteristic of that species. In the species here described this muscular impression extends slightly more than half the length of the shell and is divided by a prominent median ridge. The brachial valve shows a slight rounded median ridge which extends about a third of the length of the shell and is continued backward into the cardinal process. The muscular impression in this valve is poorly defined. The crural processes are prominent as in *R. vanuxemi.* While this form resembles closely *R. vanuxemi* it is somewhat intermediate between that form and *R. penelope.*

Horizon and locality.—Amherstburg dolomite, Stony Island Dry Cut in Livingston Channel, Detroit River, near Trenton, Michigan.

Schizophoria prima n.sp.

Plate II, Fig. 3

Shell transversely elliptical or roundly quadrate, moderately convex. Hinge line approximately straight and equal to about half the width of the shell.

Brachial valve unknown. Pedicle valve with rather prominent umbonal region and sloping abruptly to the cardinal area and extremities. In other directions from the umbonal area the valve is more or less flattened (possibly accidentally) but abruptly curved downward at the margins. The front third shows a broad ill-defined sinus which makes but a slight impression on the front margin. Surface marked by fine radiating striae, which are poorly shown on the internal mold. Concentric growth lines are also visible.

The internal impression of the pedicle valve shows a rather small subquadrate muscular scar, which is bordered by a deeply impressed

margin and partially bisected by a prominent rounded ridge impression. This latter was apparently longitudinally striated while the muscular scars themselves were concentrically marked.

Horizon and locality.—Amherstburg dolomite, Stony Island Dry Cut, Livingston Channel, Detroit River, near Trenton, Michigan.

Stropheodonta delicatula n.sp.

PLATE II, FIGS. 4 AND 6

Shell semi-elliptical, somewhat wider than long. Cardinal extremities produced, hinge line usually greater than the greatest width of the shell.

The specimens found are chiefly brachial valves and of those only the external impression, with rarely a rather poor preservation of the shell. Fragments of the pedicle valve show that it was regularly convex and rather gibbous. The beak was small and slightly incurved and extending beyond the area as in *Stropheodonta demissa.* Brachial valve moderately to deeply concave, usually following rather closely the inside curvature of the pedicle valve, leaving scarcely a sixteenth of an inch as the probable thickness of the animal.

Area of pedicle valve arcuate and more or less triangular; area of the brachial valve apparently flat and uniform in width.

Surface of valves marked by strong radiating striae, rather distantly spaced, and between which are numerous fine striae. In the umbonal region the surface is marked by distinct ribs or costae, which seem to persist for half an inch or more from the beak and then are gradually lost. These radiating surface ornamentations are crossed by numerous growth lines which are occasionally aggregated into more conspicuous wrinkles. This species may be compared with *Stropheodonta galatea.*

Horizon and locality.—Amherstburg dolomite, Stony Island Dry Cut, in Livingston Channel, Detroit River, near Trenton, Michigan.

Nucleospira livingstonensis n.sp.

PLATE II, FIG. 6

Shell nearly circular in outline, rather gibbous and rounded oval in transverse section. Width and length nearly equal.

Hinge line about one-third the width of the shell. Cardinal area very narrow and inconspicuous.

Brachial valve not known. Pedicle valve showing a lightly impressed muscle scar and a distinct median septum, which latter is traceable about one-half the length of the shell.

Surface showing distinct growth lines and rather indistinct radiating markings. These latter can hardly represent the surface spines, but suggest them.

Horizon and locality.—Amherstburg dolomite, Stony Island Dry Cut, Livingston Channel, Detroit River, near Trenton, Michigan.

Loxanena inculta n.sp.

PLATE II, FIGS. 7 AND 8

Shell tapering gradually to a high spire; apical angle 35°. Six or more volutions which are moderately convex or somewhat flattened on the outer surface but rather abruptly curving on the lower side of the whorl. Aperture subelliptical. Surface marked by strong regularly elevated striae, which turn gently backward from the suture and then forward, completing the curve before the periphery of the whorl is reached and below which they have been preserved.

Horizon and locality.—Amherstburg dolomite, Stony Island Dry Cut, Livingston Channel, Detroit River, near Trenton, Michigan.

Callonema perlata n.sp.

PLATE III, FIGS. 1 AND 2

Shell depressed turbinate; spire low, consisting of five or more volutions which increase in size gradually and are oval in cross-section. Apical angle 138°. Umbilicus large and shallow. Suture moderately depressed and marking the outer margin of the preceding whorl.

Surface marked by medium to coarse striae of growth, which pass obliquely outward from the suture, continue over the periphery, from which they curve gently backward, and then disappear in the umbilicus. The coarseness of the striae increases with distance from the apex of the spire.

Horizon and locality.—Amherstburg dolomite, Stony Island Dry Cut, Livingston Channel, Detroit River, near Trenton, Michigan.

DESCRIPTION OF PLATES

All figures are natural size.
Mr. G. S. Barkentin, delineator.

PLATE I

Fig. 1. Arachnocrinus *ignotus* n.sp.
1. Dorsal (?) view.

Figs. 2–5. *Poterioceras canadensis* n.sp.
2. Ventral view.
3. Dorsal view.
4. Lateral view.
5. Posterior view of the last chamber preserved and showing position of siphuncle.

PLATE II

Figs. 1–2. *Rhipidomella intermedia* n.sp.
1. Brachial valve.
2. Pedicle valve of same specimen.

Fig. 3. *Schizophoria prima* n.sp.
3. Pedicle valve.

Figs. 4–5. *Stropheodonta delicatula* n.sp.
4. Impression of brachial valve showing impression of part of cardinal area of pedicle valve.
5. Impression of brachial valve of another specimen.

Fig. 6. *Nucleospira livingstonensis* n.sp.
6. Pedicle valve.

Figs. 7–8. *Loxonema inculta* n.sp.
7. A small specimen showing surface markings fairly well preserved.
8. A large specimen showing surface poorly.

PLATE III

Figs. 1–2. *Callonema perlata* n.sp.
1. Lateral view showing character of surface markings.
2. Apical view.

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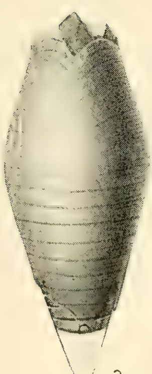

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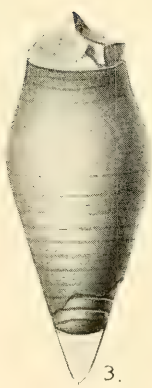

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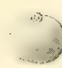

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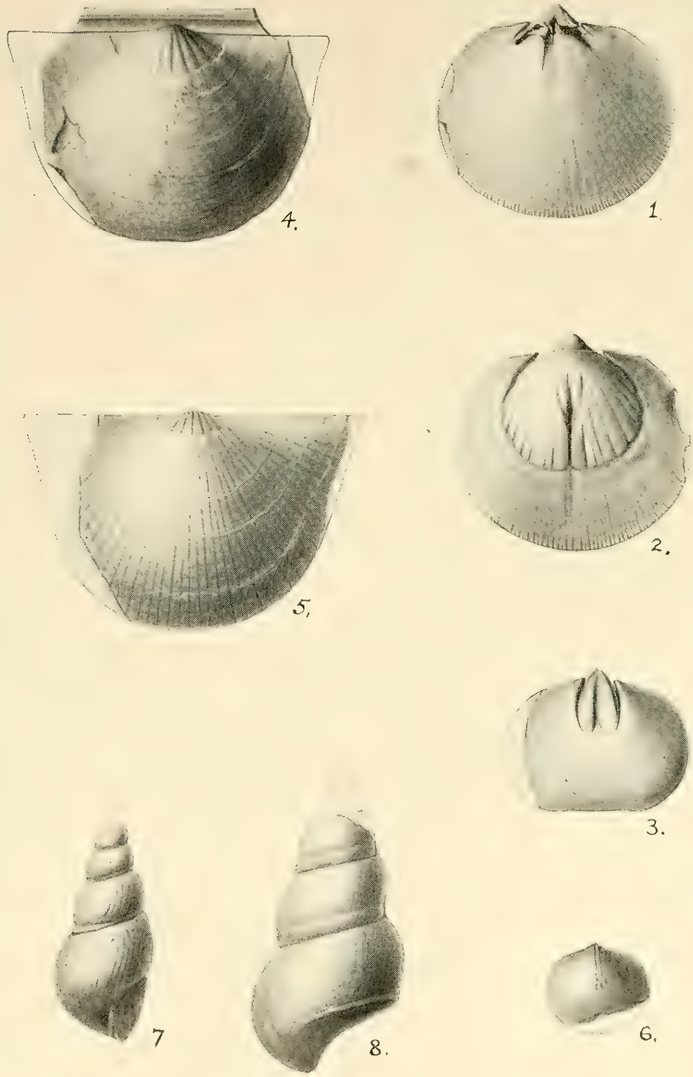
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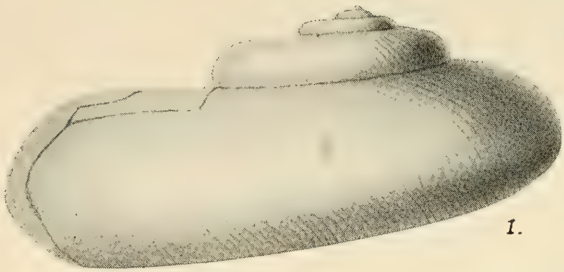

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ON THE NATURE AND ORIGIN OF THE STYLOLITIC STRUCTURE IN TENNESSEE MARBLE[1]

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CONTENTS

INTRODUCTION

The stone known commercially as "Tennessee marble" constitutes what the government geologists have called the Holston formation, which is of Ordovician age. The quarries are located chiefly in the central portion of the East Tennessee Valley with Knoxville as a center. The marble is sub-crystalline to crystalline in texture and varies in color from light pink and gray to differing shades of red, dark chocolate, and cedar. At present the light pink and gray are the varieties most in demand. The formation is from 200 to 400 feet thick, though by no means is all of this suitable for decorative purposes. As a result of folding, accompanied in places by faulting, the outcrops occur in belts extending from northeast to southwest. The strata dip usually 25 to 35

[1] Read before the Tennessee Academy of Science, November 26, 1915, and the American Association for the Advancement of Science, Pittsburgh, December, 1917. (Abstract, *Science*, New Series, XLVII [1918], 492.)

degrees to the southeast, but in places they are inclined in the opposite direction. The marble takes a fine polish and is much favored by architects for interior decoration. It is widely used for both interior and exterior work and may be seen in many buildings throughout the United States and even in foreign countries.

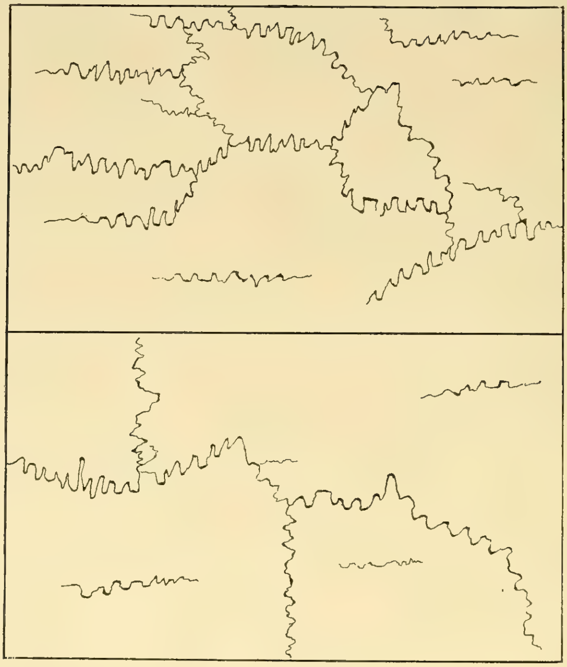

FIG. 1.—Examples of Stylolites in Tennessee Marble

One of the striking features of the marble is the presence of dark-colored, interlocking seams or sutures known technically as "stylolites." This structure, which is prominently displayed on the polished surfaces of slabs cut across the bedding planes of the stone, is known among the quarrymen as "crowfoot" and "toe-nails," and various theories have been proposed to account for it. It first attracted attention in the Muschelkalk of Europe but has been observed to occur in limestones generally, though some of the best examples appear in the Muschelkalk of Europe, the Clinton

limestone of New York, the Bedford limestone of Indiana, and the Tennessee marble.

CHARACTER OF THE PHENOMENA

Early observations, and names applied to it.—According to Rothpletz this structure was first mentioned by Mylius in 1751. In 1807 Friesleben described it as "apfenförmiger Strictur der Flözkalkstein," and later Hausman referred to it as "Stängelkalk." The name "lignilites" was applied to these structures by Eaton in 1824. In 1838 they were called "epsomites" by Vanuxem, who likened them to the sutures of the human cranium, while Hunt gave them the name "crystallites" in 1863. The name "stylolites," from *stulos*, "a column," was given them by Kloden in 1828.

Description of the structure in Tennessee marble.—The sutures present in Tennessee marble have the typical appearance of "stylolites" as described by authors. They consist of slickensided columns of stone projecting alternately from the surfaces on either side of a parting or fracture plane whereby the two parts of the stone become intimately interlocked. As a rule the union is so intricate and firm that the stone will break more readily elsewhere than along the suture. The columns vary in length from a small fraction of an inch to four inches or more, and in diameter they may be two inches or more, though usually they are much under this. The sides of the columns are fluted and striated in the manner characteristic of "slickensides." Occasionally the columns are broad and relatively short with tops studded with the small projections. The columns are usually capped with a thin layer of clay. In places the clay is more abundant and in such cases may weather out in the cliff, leaving cavities. The occurrence of a shell or other fossil capping the column is frequently mentioned by authors but such instances are rare in the Tennessee marble.

In general the sutures are approximately parallel with the planes of bedding, but frequently they may be observed cutting the planes of sedimentation obliquely or even at right angles. In places they appear as a network intersecting the stone in all directions. In some portions of the rock the horizontal sutures are numerous and closely spaced while in others they are several feet apart. In the

majority of cases they thin out without a trace of parting beyond, but not infrequently they are terminated abruptly by a cross-fracture or suture. Branching of the horizontal sutures is common and often the two branches meet again, thus inclosing lens-shaped masses of stone.

On surfaces showing both horizontal and oblique sutures it is observed that the columns are all at right angles to a common plane which is approximately the plane of sedimentation. In their descriptions of stylolites, Marsh, Grabau, and others state that the columns project at right angles from the opposing faces, but this is true, according to our observations, only of those sutures that follow the planes of sedimentation. Where the suture is oblique to this plane the columns are inclined, the inclination being greatest in those sutures which are most oblique to the plane of sedimentation. Where the suture is at right angles to the plane of sedimentation, distinct columns are wanting, the suture appearing as a wavy or zigzag line apparently representing the variety of stylolitic structure termed "pressure-suture" by some authors.

THEORIES OF ORIGIN

Only brief mention will be made here of the earlier suggestions offered in explanation of this structure. Those desiring a fuller treatment are referred to Wagner's exhaustive paper,[1] which includes a fairly complete bibliography of the subject.

Organism theory.—Eaton,[2] who appears to have been the first to offer an explanation of these structures, considered them to be of organic origin and named them "lignilites" in the belief that they were the columns of corals. Four years later, Kloden[3] described them as a distinct species of organism under the name *Stylolites sulcatus*. These, however, had few followers, though Kloden's name "stylolites" has been retained for the structure.

Crystallization theory.—Bonnycastle in 1831 considered the structure as a mineral formed by infiltration. The mineral expla-

[1] Georg Wagner, *Geologische und paleontologische Abhandlungen* (Koken), N.F. (1913), Band XI (XV), Heft 2, pp. 101–27, Plates X, XI, XII.

[2] Amos Eaton, *Geology of New York*, 1824.

[3] F. Kloden, *Die Versteinerungen der Mark Brandenburg* (1828), 1834.

nation was accepted in 1838 by Vanuxem and the name "epsomites" applied to the structure in the belief that it represented the crystallization of sulphate of magnesia. Among others who accepted the mineral theory with modifications were James Hall, Ebenezer Emmons, and T. Sterry Hunt, the last named proposing for them the name "crystallites."

Pressure theory.—The first to suggest that this structure is due to differential compression of sediments before consolidation was Quenstedt,[1] followed soon after by Marsh.[2] Experimental demonstration of the theory was attempted by Gumbel,[3] but as Wagner points out the results were not convincing.

Following Marsh's explanation it is assumed that a thick bed of carbonate of lime is deposited as a fine soft ooze over the surface of which are scattered the remains of organisms, such as shells, etc. This is then covered by a very thin layer of argillaceous mud, upon which is deposited more calcareous material, whose increasing weight tends to condense the mass below. As a result of the resistance offered by the shell or other organic substance "the surrounding material will be carried down more rapidly, thus leaving columns projecting above, each protected by its covering and taking its exact shape from its outline." According to this theory, therefore, the structure is due to differences in the amount of compression in the material beneath and around the shell before consolidation as a result of the weight of the overlying mass. The fact that the columns are not always capped by shells (in Tennessee marble rarely), and, further, as pointed out by Grabau,[4] that there is no evidence of deformation, or crowding or squeezing around or above the columns, is against the theory of simple compression either before or after consolidation. Moreover, the fact that the sutures are often oblique or even at right angles to the plane of sedimentation is clearly opposed to this theory. The occurrence of such

[1] A. Quenstedt, *Epochen der Natur*, 1861, pp. 200, 489.

[2] O. C. Marsh, *Proceedings of the American Association for the Advancement of Science*, XVI (1867), 135–43.

[3] Gumbel, *Zeitschr. Deutsch. geol. Ges.*, 1882, p. 642; *ibid.*, 1888, p. 187.

[4] A. W. Grabau, *Principles of Stratigraphy*, 1913, p. 787.

transverse sutures was observed by Marsh, but he seems to have failed to recognize their negative bearing on the pressure theory.

Gas theory.—Zelger,[1] in 1879, after detailed work on the stylolites considers them due to the escape of gases through the soft plastic mass and the later filling in of the passageways.

Erosion theory.—In his description of this structure as it occurs in the Bedford limestone of Indiana, Hopkins[2] reviews the theories given therefor and suggests that some may be due to the formation of cracks in the drying of limestone mud while others look like a rain- or spray-washed surface, though he adds that "possibly the escape of gases, as advocated by Zelger, may have acted in some places."

Solution theory.—The theory that the stylolitic structure is due to unequal solution along suture or fracture planes in calcareous rocks after consolidation was first proposed by Fuchs,[3] later accepted by Reis,[4] and more fully established by Wagner.[5] Quoting from Grabau,[6]

> if solution takes place on the concave surfaces of both the upper and lower faces of the fracture, the result must be the production of a series of tooth-like projections from both sides of the fissure, which, owing to the pressure of the overlying rock, interpenetrate more and more as room is made by solution. In other words the rock opposite the end of each tooth-like projection is dissolved away—the hollows are deepened and the teeth, gliding under pressure, penetrate deeper and deeper into the opposite bed while at the same time they become longer by the deepening of the hollows which surround and isolate them. The residual clay left on solution comes to rest as a cap on the top of the stylolite protecting this top from solution.

The striations on the sides of the stylolite are the result of abrasion between the opposing surfaces in the process of compression. As the sides of the columns are largely free from pressure there is little or no solution there. The presence of a shell or other fossil favors the process, as it is less readily soluble than the inclosing rock.

[1] Zelger, *Neues Jahrb. für Mineralogie*, 1870, p. 833.

[2] T. C. Hopkins, *Twenty-first Annual Report of the Indiana Geological and Natural History Survey*, 1896, pp. 305–8.

[3] T. Fuchs, *Ber. d. K. Akad. d. Wiss. Math. nat. Kl. Wien*, 1894.

[4] O. M. Reis, *Geognost. Jaresh. d. K. Bayr. Obergamtes München*, Band 14, 1901; also Band 15, 1902.

[5] Georg Wagner, *op. cit.*

[6] A. W. Grabau, *op. cit.*

It is held by some that the sutures seen in Tennessee marble represent original stratification planes or partings which are occupied by very thin laminae of silt, and beneath this silt unequal solution has taken place as indicated above. That the opposing faces along clay partings in limestones are affected by unequal solution is a matter of common observation. Often the opposing surfaces of the beds will be seen to have rounded elevations and depressions which alternate with each other, but there is no interlocking as in the case of true stylolites. If the clay parting is very thin, however, it is quite likely that a true stylolitic structure may develop along such planes, and that some of the sutures in Tennessee marble are of this character is probable. But from the study of hundreds of examples of the sutures in the Tennessee marble, the writer is convinced that in the main they represent fracture planes. Convincing proof of this appears in their irregularity and frequent tendency to cut across the sedimentation planes obliquely or even at right angles. Wagner, who described them as occurring along fractures, stressed this point when he says that, whereas under the pressure theory the sutures must follow the plane of sedimentation, in the solution theory they may intersect the stone in any direction.

Inasmuch as the columns manifest a general tendency to assume a position at right angles to the plane of sedimentation and since it is probable that static as opposed to dynamic pressure has been most effective in furthering solution this would seem to offer evidence that the stylolitic structure was more or less advanced if not completed before the rocks assumed their present tilted position as a result of folding and faulting at the close of the Paleozoic era.

Grabau considers that the length of the column is a fair measure of the amount of material removed from both sides of the fracture.

SUMMARY

Polished slabs of Tennessee marble are usually marked by irregular zigzag lines likened by Vanuxem to the sutures of the human skull and now known generally as "stylolites," the origin of which is a subject of frequent inquiry. These structures consist of striated

toothlike projections or columns projecting from the opposing surfaces along a plane of fracture whereby the two parts of the stone are so intimately interlocked that often the slab will break more readily elsewhere than along the suture.

The theory that they are due to differential compression in beds of soft calcareous sediments separated by a thin film of clay was first proposed by Quensted (1861) and adopted by Marsh (1867), Gumbel (1882), Rothpletz (1900), and others. The absence of evidences of compression and squeezing as also the fact that the sutures are often more or less oblique to the planes of sedimentation or may form a network of intersecting lines are adverse to this theory.

The most satisfactory explanation of these remarkable structures is the solution theory first proposed by Fuchs (1894) and ably supported by Reis (1901, 1902) and Wagner (1913). According to this theory the structures are due to unequal solution along planes of fracture, or extremely thin partings after the consolidation of the rock. As the result of compression due to the weight of the overlying mass, solution will take place more rapidly on the concave surfaces opposite the columns, thus causing these to penetrate deeper and deeper into opposing surface. The residual clay comes to rest as a cap on the top of the column, thus protecting it from solution. Fossil shells sometimes found on top of the column favor the process, as they are less readily soluble than the inclosing rock.

THE VALLEY CITY GRABEN, UTAH[1]

C. L. DAKE
Rolla, Missouri

During the course of reconnaissance work undertaken in 1917 over much of southern Utah, the writer observed an interesting structure which seems worthy of a brief description. It is located in Townships 22 and 23 South, Ranges 19 and 20 East, in Grand County, and is plainly visible along the road between Thompsons and Moab, near Valley City.

STRATIGRAPHY

The stratigraphy of the general region is simple, and is well described in reports by Lupton[2] and Woodruff,[3] to which the reader is referred for greater detail. The oldest formation exposed in the immediate vicinity is the Dolores, consisting of about 1,300 feet of variegated sandy shales and soft sandstones of Triassic age. Red, pink, and gray are the dominating colors. The formation is relatively nonresistant, and usually comprises plains and broad valleys. Above the Dolores occurs the La Plata sandstone, probably Jurassic in age. This is the most prominent formation in the district, and consists of two tan-colored, massive, highly cross-bedded sandstones separated by about 100 feet of red sandy shale. The sandstones are prominent cliff-makers and form the pronounced fault-line scarp near Court House Spring on the Thompsons-Moab road. Occasional lenses of unfossiliferous limestone a few feet thick and a few yards in extent were noted in the sandstone in places. Above the La Plata sandstone occurs the McElmo formation, of Jurassic age, consisting of about 1,000 to 1,200 feet

[1] Published by permission of Valerius, McNutt, and Hughes, Consulting Petroleum Geologists, Tulsa, Oklahoma.

[2] C. T. Lupton, "Oil and Gas near Green River, Grand County, Utah," *U.S. Geol. Survey, Bull. 541* (1914), p. 115.

[3] E. G. Woodruff, "Geology of the San Juan Oil Field, Utah," *U.S. Geol. Survey, Bull. 471* (1912), p. 76.

of shales and sandstones. No fossils were noted in this vicinity, but near Teasdale, in Wayne County, the writer found abundant marine fossils, chiefly pentagonal crinoid stems in a thin limestone, a few feet above the contact of this formation with the underlying massive sandstones. Fossils were also found at the same horizon near Loa. The McElmo beds are highly variegated, red, pink, gray, green, and maroon being common shades. Gypsum, in beds up to 100 feet or more thick, occurs in the lower half of the formation. About 400 feet below the top of the McElmo occurs the Salt Wash member, a very conglomeratic gray coarse sandstone. The McElmo has a highly characteristic bad-land topography. Following the McElmo occurs the Dakota formation of Cretaceous age, usually 25 or 30 feet thick, a coarse gray sandstone, at places highly conglomeratic and outcropping in hogbacks. Above the Dakota is the Mancos, a bluish-gray soft shale 2,000 to 3,000 feet thick, forming broad plains.

STRUCTURE

Lupton,[1] on his map of the Green River field, does not show the formations in the area involved in this description, but he writes the word "anticline" along the axis of the structure in question, leaving the area blank, since it was outside the field involved in his report. As seen from the west, along the Green River-Moab road or the Thompsons-Moab road (Fig. 1), the structure appears to be a simple anticline, the limbs of which rise gradually from the adjacent plain of Mancos shale to the northeast and southwest. Two scarps about a mile apart face each other from these limbs and overlook a central or axial valley which strikes about N. 45° W. At first this was supposed to be a simple anticlinal valley, but the extreme straightness of these scarps for several miles aroused suspicion, so a careful examination of the structure was made. It was found to be a well-developed anticline, along the crest of which occurs a typical graben or down-faulted trough about a mile wide (Fig. 2.). The relationships are clearly brought out in Figs. 3 and 4. Outcrops of Mancos shale were found almost in contact with La Plata sandstone. This would give the fault a displacement of perhaps 1,200 feet or

[1] *Loc. cit.*

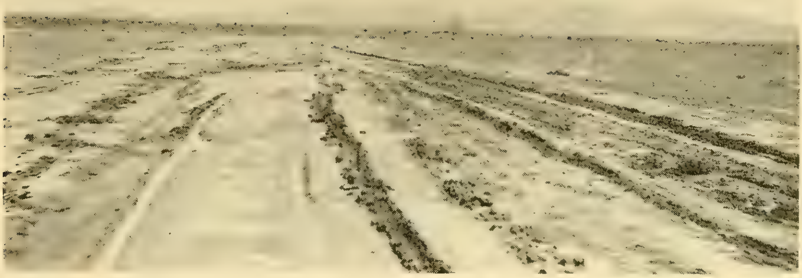

FIG. 1.—The Valley City anticline, seen from about three miles west of Valley City, Grand County, Utah.

FIG. 2.—Within the graben of the Valley City anticline, Grand County, Utah. The walls on either side are fault-line scarps.

more. No fossils were found in the Mancos, but it is so highly characteristic in color and texture as to afford little doubt of its proper identification. Still farther southwest the graben seems to be floored with McElmo beds, probably the Salt Wash member,

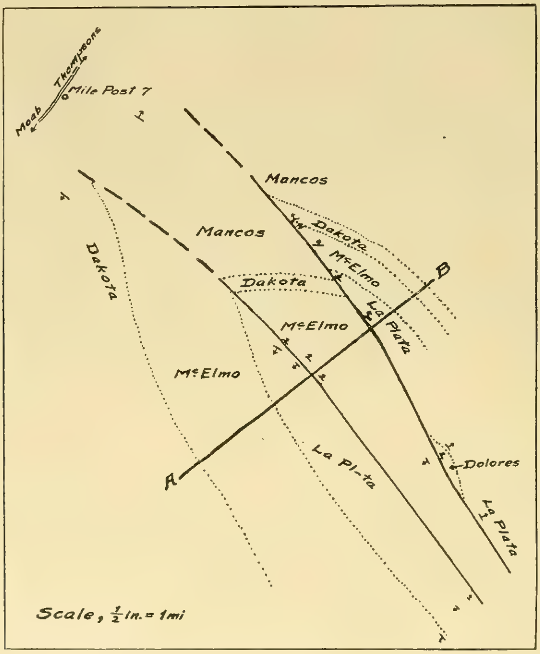

FIG. 3.—Map of portion of Valley City graben, Utah

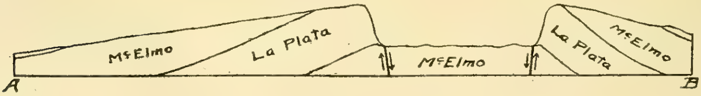

FIG. 4.—Section across Valley City graben, Utah

consisting of coarse gray conglomeratic sandstone. While it is possible that these beds are Dakota conglomerate, from their general character it seems much more probable that they are Salt Wash. They lie at the base of a well-pronounced fault-line scarp of La Plata sandstone several hundred feet high, along the base of which the Dolores is probably exposed. If so, this would involve about 2,000 feet of displacement.

Along the bottom of the graben plain, toward the base of the scarps on both sides, the beds show high local dips that are presumably the result of drag along the fault planes.

While the identification of the beds in the graben plain was wholly on lithologic grounds and was rendered somewhat difficult by scarcity of outcrop, there seems to be little doubt that the foregoing interpretation is the proper one. And while grabens are by no means rare, a graben occupying the axial line of a well-defined anticline seems sufficiently unusual to merit some attention. The area is probably complicated by cross-faulting. Since only one day was spent studying the structure, it is more than probable that important features escaped detection. The entire region is one that offers possibilities of interesting structural and stratigraphic work.

The topographic expression of this structure is clearly shown on the old United States Geological Survey La Sal Reconnaissance sheet, east of the road leading from the railroad to Moab. The two inward-facing scarps with the central valley and the outward dip slopes are plainly marked.

While no detailed work was done at Moab, the writer has seen some evidence to lead to the conclusion that the Moab plain, extending southeast from the village of Moab, is possibly also a similar graben.

REVIEWS

Chemical Analyses of Igneous Rocks. Published from 1884 to 1913 Inclusive. By HENRY STEPHENS WASHINGTON. U. S. Geol. Survey, Prof. Paper 99. Washington: 1917.

Students of petrology are still further indebted to Dr. Washington for a great store of chemical data in the form of 8,602 rock analyses, gathered together from all manner of geological and petrographical publications and from personal contributions of analyses which were awaiting publication. The value of such a carefully prepared and vast accumulation of rock analyses is obvious to all who desire to know the chemical composition of igneous rocks and wish to compare the rocks of different regions. The labor involved in collecting and arranging the analyses and in calculating the mineral norms is indicated by the statement of the author that "on an average the 4,980 analyses in Part I took 45 minutes apiece and those in Parts II, III, and IV (3,622) took about 30 minutes or more apiece," in all more than 5,546 working hours.

The analyses have been arranged according to their quality in four groups: (I) superior analyses of fresh rocks, designated as "excellent," "good," and "fair," except those which could not be classified properly in the quantitative system of rock classification; (II) superior analyses, generally good or fair, not properly classifiable in the quantitative system; (III) superior analyses of tuffs and of weathered or altered rocks; (IV) analyses deemed poor or bad. Nearly 5,000 analyses have been classified and arranged according to the quantitative system of classification of igneous rocks, and form the major portion of the collection, which includes those in the first collection by Dr. Washington, published as *Professional Paper 14*, in 1903. The new publication is a revision and expansion of the former, in which Part I contained 1,711 superior analyses. The amount of expansion is shown by a comparison of the number of analyses published in each paper. In No. 14 the total was 2,881, of which 1,711, or 59 per cent, were placed in Part I. In No. 99 the total is 8,602, of which 4,980, or 58 per cent, are put in Part I. There are 5,721 more in the new collection, or nearly three times as many as in the former one. This shows an increased production in

thirteen years of double that of the previous sixteen years and a betterment of the quality, since nearly 1,500 superior analyses are placed in Parts II and III of the new collection; that is, 6,471 superior analyses were made in the thirteen years since 1900.

The text contains a critical discussion of the character and use of analyses: their representativeness, accuracy, and completeness. The method by which the author rated the analyses is explained. It is this rating, which was employed in the earlier publication, that has had much to do with the marked improvement in more recent analytical work. An inspection of the geographical distribution of the localities from which rocks have been analyzed shows some extensive gaps, even in regions accessible to petrographers, as the author points out. There is an important commentary on names that have been applied by various petrographers to divisions of the Quantitative System of Classification, as well as a concise statement of the Quantitative System, and of the method of calculating norms from chemical analyses, besides numerical tables for use in the calculation. It would be a great help to petrographers if this portion of the book were printed and published separately.[1] The thorough indexing of the book according to four systems adds greatly to its usefulness.

J. P. Iddings

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THE ECOLOGICAL SIGNIFICANCE OF THE EAGLE CREEK FLORA OF THE COLUMBIA RIVER GORGE

RALPH W. CHANEY
University of Iowa

INTRODUCTION

During the seasons of 1916 and 1917 considerable collections of fossil plant material were made by the writer in the gorge of the Columbia River, in Oregon and Washington. It has been planned to present a complete report on this material, including a description of new forms, a discussion of the age of the flora, and a consideration of its ecological significance. In view of the possible interruption of this larger task a discussion of the ecological significance of the flora is presented in advance of the fuller report.

Acknowledgment is made to Dr. J H. Bretz, of the University of Chicago, who first directed the writer's attention to this field, and who is responsible for the discovery of one of the most important plant-bearing deposits. I am indebted also to Dr. F. H. Knowlton

for valuable advice and assistance in determining species, and to Dr. H. C. Cowles, of the University of Chicago, for his direction in the interpretation of the ecological data. The work during the season of 1917 was carried on with the aid of a grant from the Research Fund of the American Association for the Advancement of Science, to which organization sincere acknowledgment is due.

GEOGRAPHIC LOCATION AND TOPOGRAPHIC FEATURES OF THE COLUMBIA GORGE

The gorge of the Columbia River is that portion of its valley in the Cascade Range. Its general features are shown in the Mt. Hood sheet of the United States Geological Survey, where the Columbia River forms the boundary between Oregon and Washington. The river has exposed here a section which has a maximum thickness of over 4,000 feet. The basal Eagle Creek formation is displayed at the axis of the range, giving the most complete section just west of the boundary between Multnomah and Hood River counties. The total length of the gorge from Troutdale, Oregon, on the west to The Dalles, Oregon, on the east is about 70 miles. Its width averages about one mile.

The walls of the gorge rise steeply, especially on the Oregon side, where cliffs of basalt rise more than 2,000 feet almost vertically. A number of peaks, some of them representing volcanic cones, lie a short distance back from the edge of the walls. Larch Mountain, 4,045 feet, and Mt. Defiance, 4,960 feet, are conspicuous examples. Numerous small tributary streams flow into the Columbia from each side through canyons which are much shallower than that of the master-stream. As a result each has at or near its mouth a falls or series of falls, the highest being Multnomah Falls, 620 feet high, at the mouth of Multnomah Creek. The sections exposed in the lower stretches of these tributaries add much to our knowledge of the stratigraphy and fossil content of the rocks.

The western two-thirds of the gorge is occupied by the luxuriant forest of Douglas spruce so characteristic of the Pacific coast. Much of the geologic record is hidden by the density of this forest and its undergrowth. The best accessible sections are found where the building of roads and trails has temporarily destroyed the

vegetation cover. Conditions become progressively more arid toward the east, with only a sparse occurrence of pines and oaks at The Dalles.

GEOLOGIC RELATIONS OF THE EAGLE CREEK FORMATION

A recent study of the geology of the Columbia River Gorge by Drs. I. A. Williams and J H. Bretz under the auspices of the Oregon Bureau of Mines has given us a rather complete knowledge of the general geology of this little-known region.[1] As far back as 1873 LeConte recorded the presence of fossil leaf impressions in the volcanic conglomerate at the base of the basalt series.[2] In 1895 Diller secured a small collection of leaves near the mouth of Moffatt Creek which has been described by Knowlton,[3] and four years later Gilbert made a larger collection from a talus block near Cascade Locks, a collection which has never been described. The collections which are the basis of this paper are, however, the first which are sufficiently complete to give any conclusive evidence regarding the age of the Eagle Creek formation.

There are but few cases of such an illuminating record of the history of a mountain range as has been furnished by the Columbia River in its path across the Cascades. Following is the generalized section exposed by the Columbia: gravels and river terraces of recent origin; Herman Creek lava—andesitic basalt; Satsop formation—stream gravels and volcanic ash; Columbia River lava—successive flows of basalt; Eagle Creek formation—volcanic conglomerate, ash, and tuff.

The Eagle Creek formation.—The Eagle Creek formation is exposed along the bottom of the gorge from Warrendale to Viento on the Oregon side with a corresponding distribution on the north side of the river. It is the oldest formation recognized in the region, and is brought to the surface in the axis of the great north-south anticline which is the backbone of this portion of the range. The thickness of the exposed part of the formation varies from 2,700

[1] Ira A. Williams, *Bull. of the Ore. Bureau of Mines and Geol.*, Vol. II, No. 3, 1916; J H. Bretz, unpublished manuscript.

[2] J. LeConte, *Am. Jour. Sci.*, 3d Series, VII, 167–80.

[3] F. H. Knowlton, *Twentieth Ann. Rept. U.S. Geol. Surv.*, pp. 37–64.

feet at Red Bluffs on the Washington side to 500 feet on the Oregon at Bonneville, a condition which appears to be due in part at least to the southward plunge of the fold.

The formation as exposed on Table Mountain and Red Bluffs comprises a series of beds of tuff, ash, and volcanic conglomerate, the conglomerate being most conspicuous near the top. In several of the talus masses of the conglomerate poorly preserved leaf impressions are found, and in both the conglomerate and the tuff silicified wood is common. To the west of Red Bluffs cliffs of conglomerate are conspicuous, and from them have slumped the great masses of rock which have dammed the Columbia River, resulting in its cascades. The base of the formation is reached neither on the Washington nor on the Oregon side.

On the Oregon side the maximum section exposed, 500 feet thick near Bonneville, is a volcanic conglomerate, in most places highly indurated. All the bowlders are of porphyritic basalt, some of them reaching a diameter of 15 feet and averaging from one to three feet in the coarser phases of the formation. The matrix is a fine to coarse volcanic sand. Numerous pockets and lenses of shale and sandstone are a characteristic feature. These are of slight extent both vertically and horizontally, and in many cases contain more or less well-preserved leaf impressions. Silicified logs and carbonized stems and fragments are of common occurrence, representing driftwood deposited with the sediments.

The frequence of volcanic activity during the deposition of the sediments is indicated by the seams of volcanic ash which are seen to overlie some of the soil layers representing old surfaces. A quarter of a mile east of Bonneville occurs what is most probably a contemporary extrusion of basalt, and on Greenleaf Creek the sedimentaries are intruded by basalt. In these situations and elsewhere locally the beds have been contorted and shattered, with the development of slickensided surfaces and contact metamorphism.

The upper surface of the Eagle Creek formation, overlain by basalt flows, is markedly irregular, as first noted by LeConte in the canyon of Tanner Creek.[1] Evidences of intraformational unconformities are numerous and will be discussed below.

[1] *Op. cit.*

Collections of leaf impressions were made in eighteen localities, ranging from the mouth of Moffatt Creek on the Oregon side of the gorge to the foot of the cliffs at Red Bluffs in Washington, six miles distant. These collections, while made up of rather fragmentary material on the whole, include remarkably well-preserved leaves where the matrix is a fine clay. In most situations the leaves were secured just above a layer of carbonaceous shale which represents the old soil line, in the fine sandy or shaley material laid down upon the old surface.

The following description of a locality on the Columbia River Highway shows the typical occurrence of the fossil plants: 850 feet

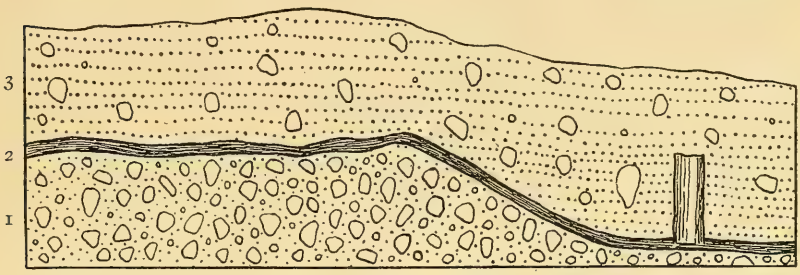

FIG. 1.—Section of the Eagle Creek formation 850 feet west of the Tanner Creek bridge on the Columbia River Highway, showing relations of the soil line and the upright tree.

west of the Tanner Creek bridge on the Columbia River Highway, a bed of cobble conglomerate 20 to 25 feet in thickness is overlain by a carbonaceous seam containing leaves. The general relations are shown by Fig. 1. Here bed 1 is a layer of coarse conglomerate which is overlain by bed 2, a seam of carbonaceous sandy shale from 8 inches to 3 feet in thickness. Overlying bed 2 and inclosing the fossil tree which is rooted in the shale is bed 3, comprising 15 feet of sandstone containing numerous bowlders.

The upper surface of 1 is suggestive of an erosion surface on which several feet of soil 2 accumulated. The upright tree appears to have been growing in a valley cut in 1 during the time of the soil accumulation, and about its roots numerous leaves have been buried and fossilized.[1] The lack of another slope makes the

[1] A microscopical examination of this fossil wood has not yet been made to determine its taxonomic relations.

assumption of a valley uncertain, but in any case the sloping soil line establishes the fact that this old land surface had considerable relief at the time 3 was deposited on it.

The age of the Eagle Creek formation has been imperfectly known, due to the small amount of fossil material previously secured from it. On the basis of these more extensive collections it will be possible to fix the age with reasonable certainty. At present the age may be referred tentatively to Upper Eocene on

FIG. 2.—*Quercus pseudo-lyrata.* One-half natural size

the basis of close resemblances of the flora to that of the Upper Clarno beds of the John Day Basin and related formations in Idaho and California.

THE ECOLOGICAL COMPOSITION OF THE FLORA

It is not the purpose of this paper to describe the composition of the Eagle Creek flora from the taxonomic standpoint. It will be sufficient to note that of some 80 species represented, 75 are angiosperms, of which but 2 are monocotyledons. Following is a provisional list of the genera, with the number of species included in each: *Ginkgo* 1, *Pinus* 1, *Picea* 1, *Smilax* 1, *Cyperacites* 2, *Populus* 3, *Salix* 3, *Hicoria* 2, *Juglans* 1, *Alnus* 1, *Carpinus* 1, *Corylus* 1, *Castanea* 1, *Quercus* 12, *Ulmus* 2, *Planera* 2, *Magnolia* 1,

Laurus 2, *Platanus* 2, *Liquidambar* 3, *Crataegus* 1, *Sterculea* 1, *Rhus* 1, *Ilex* 1, *Acer* 3, and *Fraxinus* 1.

Considering the ecological composition of the flora, the outstanding feature is the presence in it of leaves which represent two distinct ecological types, one xerophytic and the other mesophytic. The former includes several species of oaks, notably *Quercus pseudo-lyrata* (Fig. 2), which is the most abundant species in the flora. The latter comprises most of the remainder of the flora, including a large number of genera and species, of which *Acer bendirei* is represented by the largest number of specimens.

FIG. 3.—*Acer bendirei*. One-half natural size.

Quercus pseudo-lyrata, the most abundant species, is found in twelve of eighteen localities furnishing leaves. Clearly the conditions under which it lived may be said to be widespread. Its leaves have the thickness and coarse epidermis which constitute the morphological expression of a xerophyte. Its modern representatives, *Q. velutina*, *Q. muhlenbergii*, and *Q. marylandica*, have their typical range in xerophytic habitats. It seems entirely probable that *Q. pseudo-lyrata* occupied a similar habitat, an exposed situation with a small amount of moisture.

Associated with this presumably xerophytic species, commonly in the same slab and almost invariably in the same locality, is *Acer bendirei* (Fig. 3), a maple closely related to *A. macrophyllum*, which is an abundant member of the flora now living in the gorge. Even were it not well known that maples are almost exclusively found in well-watered habitats, the mesophytic character of *Acer bendirei* could be ascertained from the thin texture and large size of the fossil leaves. Occurring in fourteen out of eighteen localities it is an abundant species and one which shows moisture requirements widely different from those of *Quercus pseudo-lyrata*.

There is little reason to doubt that these two ecological types represent two distinct habitats from which leaves have become intermingled and fossilized. The abundance of individual oak leaves is adequate evidence that they have not come from scattered relicts of an earlier succession which has been supplanted by one more mesophytic. On the assumption that the xerophytic leaves are xeromorphs and owe their structure to a physiologically dry habitat such as a bog, a twofold habitat would still be required, for such xeromorphic forms would not be included in the same association with typical mesophytes like *Acer*, *Ulmus*, and *Platanus*. Further, the typical xeromorphic leaf is entire-margined, while *Quercus pseudo-lyrata* has conspicuous lobes and sinuses. On the basis then of two habitats contributing leaves, we may consider the general type of topography required by the plant evidence.

In many parts of the United States today the uplands are occupied by a xerophytic oak association due to the exposure of such a habitat to the sun and the wind, and the consequent high rate of evaporation. Where such an upland is dissected by valleys, especially by those with rather deep and narrow dimensions, these more protected situations may furnish conditions favorable for the development of a typical mesophytic flora. We may have, then, as a common occurrence, a xerophytic upland association with mesophytic tracts along the streams. Leaves from the upland trees are transported widely, due to exposure to winds, and may be carried down into the valleys and mixed with those of the mesophytes growing there. Such situations are so common today that there is little danger in assuming that they were common during the Eagle Creek epoch, though the geological evidence of such topography should be forthcoming if such were the case. On the basis of the plants, however, it is reasonable to assume the existence of this upland habitat, supporting an oak forest, and occasional valleys occupied by mesophytic maples, elms, and other species.

The mixture of the xerophytic and mesophytic types of leaves may thus be explained on the basis that the former were brought in from above and mixed with the mesophytes in the valley deposits. Aside from the exposed situation of the uplands, which would

favor the wide scattering of the leaves which fell upon it, there is the added feature that the thick xerophytic leaves alone would be strong enough to undergo transportation without being destroyed. Surely we must assume that the perfect specimens of maple, sycamore, and other broad thin leaves were not transported far from the spot where they first fell. Further, the large number of mesophytic species associated with the dominant maple and elm leaves indicates that the deposits containing them were laid down in the valley where they grew.

The evidence of the plant fossils thus may be explained on the basis of a twofold habitat such as would be furnished by an upland region traversed by valleys. Whether or not this hypothesis is supported by the geological evidence may be determined by a consideration of the physical conditions which existed during the Eagle Creek epoch.

PHYSICAL CONDITIONS DURING THE EAGLE CREEK EPOCH

The Eagle Creek formation is made up entirely of volcanic materials. In the lower part, as exposed at Red Bluffs, beds of tuff and ash are most conspicuous; above, the activity of streams is evidenced by the predominance of conglomerate. Thus it is clear that early in the epoch vulcanism was the dominant process but that toward the close the streams were able to carry and assort the volcanic material as fast as it was ejected, as well as erode the lava flows bordering the craters. This sedimentary phase is the only one represented on the Oregon side of the gorge and is the source of practically all of the fossil plants.

There are several conspicuous features, applying especially to the conglomeratic phase, which require analysis. In the first place there is a predominance of coarse material—rounded bowlders ranging up to 15 feet in diameter and averaging from 1 to 3 feet. The textural range is high in any outcrop, large bowlders mingled with small, all bound together by a matrix which varies from coarse gravel to fine mud, but is commonly sandy in texture. The abundance of large bowlders and the almost entire lack of assortment point to the deposition of these sediments by streams which had high velocity.

In the second place the stratification where present is of the lens and pocket type rather than in horizontal layers. This applies to coarse as well as fine materials, but is especially conspicuous in the case of the latter. Nearly all of the sandy and shaley phases occur in the form of lenses or pockets having a horizontal distribution of a few tens of feet and a thickness, with few exceptions, of not more than 15 to 20 feet. This is suggestive of fluctuating conditions of deposition, due either to a variation in the kind of materials available for transportation by the streams, to a variation in the volume of the streams, or to a wandering of the streams over the depositing portions of their courses.

Both of these features suggest that the sedimentation was of the bajada type, like that on the flanks of the Sierras.[1] If the Eagle Creek conglomerates were laid down as alluvial fan deposits, it is clear from their thickness that they were deposited on the flanks of a range of considerable height. This brings to consideration a third feature, that of the variation of thickness in the area. At no place is the base of the formation reached, but the observed thickness at Red Bluffs is 2,700 feet, while south of the river its exposed part is little more than 500 feet thick. This variation may be explained in two ways: first, that it is due to the southward plunge of the Cascade anticline, which would carry the top of the formation down to within 500 feet of river level (assuming a dip of about 10°); and, second, that it is related to the position of the high land which was the source of the sediments, the deposits on the immediate flanks being thickest, with a thinning outward as the distance from the source increased. Assuming that the Eagle Creek conglomerates were laid down on the flanks of an east-west range, as shown by Fig. 4, there should be other evidences of the proximity of the thicker section to the flanks of the range. It is probable that this range contained the vents from which the pyroclastics were ejected. We should therefore expect to find ash and tuff more conspicuous in that portion of the bajada nearest the range. At Red Bluffs, as has been stated, ash and tuff in alternating layers comprise most of the visible portion of the Eagle Creek formation, except near the top, where conglomerate is more

[1] A. C. Trowbridge, *Jour. Geol.*, XIX, 707–47.

conspicuous. On the Oregon side, farther away from the supposed range, the amount of pyroclastic material is relatively inconspicuous, as might be expected at a distance of 6 to 8 miles from the range.

It may be suggested that the 500-foot section of conglomerate on the Oregon side of the gorge represents the upper conglomeratic portion of the Red Bluffs section, and that the ashy and tuffaceous lower portion lies below. Surely the southward dip of the overlying basalt makes this explanation of the variation in thickness plausible. On the other hand, it appears reasonable to suppose that the 500 feet exposed on the Oregon side represents more than

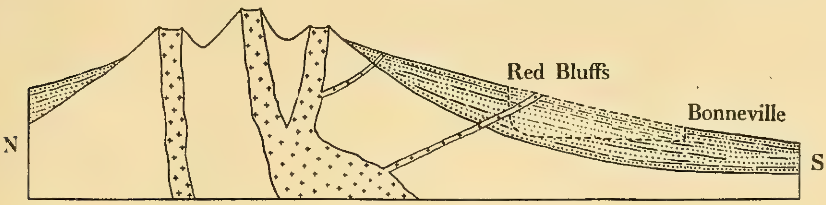

FIG. 4.—Showing the possible relations of the Eagle Creek formation on the flanks of a volcanic peak or range. The dashed line indicates the present position of the Gorge of the Columbia River in cross section.

the upper 500 feet of the Red Bluffs section. There are more intrusions in the latter, as might be expected at a point nearer the mountain range. And the paucity of plant remains in the conglomerates of Red Bluffs also has significance when it is realized that the proximity to volcanoes would probably be unsuitable for the growth of vegetation. It is of course possible that were the upper part of the Eagle Creek section readily accessible for study, plant-bearing lenses might be found in abundance there; but in all of the talus material examined at the foot of the cliffs only two masses contained leaf impressions, and these but few. The variation in thickness of the formation from north to south may then be due to a greater or less extent to the distance from the range constituting the source of the sediments.

In summary, the lithological characters of the Eagle Creek formation—its coarseness, lack of assortment, and lens and pocket stratification—point to the origin of the conglomeratic layers as a

bajada deposit on the flanks of a mountain range lying to the north, a range whose volcanoes threw out the great volume of pyroclastic material, and which later were perhaps the sources of the basalt flows. The variations in thickness from north to south are in accord with this geographic relation, for the formation appears to thin toward the south.

We may outline the physical history of the Eagle Creek formation as follows: To the north of the gorge, an east-west range of mountains contained volcanoes which were active throughout the epoch, though probably less active toward its close. Large amounts of ash and tuff were thrown out, covering the flanks of this range to a depth of more than 2,000 feet. During intervals of volcanic inactivity streams assorted this material, producing the beds of volcanic conglomerate. Toward the close of the epoch streams assumed dominance and transported large amounts of volcanic débris out from the axis of the range, depositing it as far away as the present south side of the gorge but in progressively lesser amounts. Thin layers of ash in the sections on the south side indicate that a small amount of pyroclastic material was carried there directly from the vents. The dominance of clastic sediments indicates, however, the relatively greater importance of stream deposition here, and the presence of conditions suitable for the development of plant life.

Some idea of the topographic relations of such a bajada deposit on the flanks of a high range may be gained from the description of similar deposits of the Sierras.[1] Here the alluvial plain is traversed by numerous streams flowing out at right angles from the range, streams which on losing their gradient drop their loads of coarse débris. This piles up until the deposit is considerably higher than the areas on either side, whereupon the streams are shifted laterally into the lower areas and deposition is continued there. For the purposes of this discussion it is sufficient to note that the surface of the bajada in the Sierras is characterized by numerous rather steep-sided ridges which result from stream deposition, and that most of the vegetation is found in the valley-shaped lowlands between.

[1] A. C. Trowbridge, *op. cit.*

We may now turn to the plant record to see how the biological evidence corresponds with the geological. It will be recalled that there are two distinct ecological types represented in the flora, the one composed of fewer species but including the larger number of individual leaves, indicating an exposed habitat; the other composed of many species, indicating a protected habitat. Clearly the xerophytic association would have found its place on the ridges, the mesophytic association in the depressions such as are furnished by the bajada topography. Leaves from the oaks on the ridges might easily be blown or washed into the depressions below, there to be mixed and buried with the leaves of the mesophytic maples and elms growing along the streams. The bajada topography fits well with the ecological requirements of two habitats, one exposed and xerophytic, the other protected and mesophytic.

However well these ecological requirements are fulfilled by the bajada topography, there should be some actual record of the latter if it existed during the Eagle Creek epoch. During the first season's work no such evidence was discovered. The requirements of the plants were unsatisfied until a second visit to the gorge, during which several situations were found where the topography developed during the epoch showed distinct relief. Along the Columbia River Highway cut west of the Tanner Creek bridge, two places were noted where a soil line slopes sharply into a depression. In one of these (see Fig. 1) the soil line slopes down at an angle of 22° and the depression below contains the upright stump of a large tree. Similar situations on Moffatt and Eagle creeks were observed. In the latter the material deposited over the leaf-bearing bed is clearly a valley fill, as shown by the horizontal bedding of the gravelly layers in the sandstone. Further, as previously noted, the upper surface of the formation has marked relief. Clearly the old surfaces within and at the top of the formation show that there were ridges and depressions such as the evidence of the plants demands and such as would have been present in a bajada deposit.

A consideration of the climatic conditions indicated by the plants is next in order. The numerical predominance of the xerophytic form, *Quercus pseudo-lyrata*, and its occurrence in nearly all the deposits where large collections were made indicate

that the upland conditions were such as to support an oak forest. Today the uplands, in the western part of the gorge at least, are occupied by the more mesophytic Douglas spruce (*Pseudo-tsuga*). Comparing the upland plant associations of the Eagle Creek epoch and the present, we are justified in concluding that the climate was more arid then than it is now. Looking to the mesophytic valley association of the Eagle Creek flora, the presence in it of such moisture-requiring forms as *Acer bendirei*, *Ulmus speciosa*, and others indicates that in the depressions the air was moist. This moisture was no doubt contributed in large part by the streams occupying the valleys, but the very presence of so mesophytic an association indicates that even semiaridity did not exist anywhere in the region. Rather the moisture conditions were like those at present existing in the eastern part of the Great Plains, where the mesophytes are restricted to the stream borders along the valleys because the soil there is moist. Such at least is a reasonable conjecture. The cause of the greater aridity in Eocene times than at present is not known. Presumably a mountain range to the west may have cut off the moisture-bearing winds, thus reducing the amount of rainfall, though there is no direct evidence for supposing that such a range existed.

Concerning the temperature, the presence of such tropical or subtropical forms as *Smilax*, *Sterculea*, and *Liquidambar* suggests that the climate was warmer than that in the region today. The dominance of such temperate types as *Quercus*, *Acer*, *Ulmus*, and others puts the evidence in favor of a climate which was cooling, with the resultant invasion of the tropical flora by these temperate species. Apparently the climate, while somewhat warmer, was approaching the temperature conditions of the region today.

The flora of the Eagle Creek formation gives valuable suggestions as to the length of time involved in the epoch. From a purely physical standpoint, the great thicknesses of ash, tuff, and conglomerate might have been piled up in a comparatively short time, perhaps measured in scores of years rather than in units of a larger denomination. Turning, however, to the evidence of the plants, it may readily be shown that the time required is much greater. The number of years necessary for the development of a

climax forest of a mesophytic sort is estimated to be from one to two hundred years. This is on the basis of there being no soil at the outset, and of its development through the agencies of plants and weathering. It also assumes a soil favorable for the reception of plants. In the case of the soil furnished by the Eagle Creek rocks, there was a distinct time advantage due to the fact that they were not consolidated and therefore offered an immediate foothold for rooted plants. On the other hand the chemical composition of this sediment was probably quite unsuitable for the growth of most higher plants, certainly for the growth of mesophytes. The latter require a humus content which was entirely lacking in the original volcanic materials. Further, due to its basic composition, this may be supposed to have been quite unfavorable for the development of such seedlings as germinated in it. Experimental evidence has shown that of seeds planted in pulverized Eagle Creek rock from several localities, only those of oaks (xerophytes) developed successfully. The experiments were not satisfactorily completed, and it is not known whether the oak seedlings would have continued to develop in this soil. Observational evidence from regions recently covered by volcanic ash indicate that a number of years may elapse before the return of the higher plants. It is not unreasonable therefore to assume that the full one to two hundred years would have been required for the development of a climax mesophytic forest on the volcanic débris-strewn surface during Eagle Creek times.

While it is not possible to correlate the various horizons which contain plant remains in widely separated parts of the area, due to their limited horizontal extent, it is possible to determine, on the basis of relative elevation, that there are at least ten distinct horizons represented. Each of these contains leaves of the climax forest which, as we have seen, would require from one to two centuries for its development. The total length of time involved in the growth of the ten plant horizons may thus be placed at from one to two thousand years. And when it is realized that there must be numerous other plant-bearing horizons which have not been uncovered, the length of the epoch as inferred from plant growth may be greatly extended.

CONCLUSION

Plants may, then, with a degree of caution, be used, not only to show the character of past climate, but they may also be called upon to indicate the length of time involved in a given epoch, and the general character of the topography.

In the case of the Eagle Creek flora the climate appears to have been somewhat warmer and drier than at present. The length of the epoch is to be placed at thousands rather than at scores of years. The evidence of the dominant species of plants points to the probable existence of a twofold habitat, one xerophytic and the other mesophytic. An upland cut by valley-like depressions furnishes the conditions which are thus required by the plants and at the same time fits in equally well with the strictly geological characteristics of the Eagle Creek formation.

preted as incrusted gas bubbles secondarily filled with calcite ("ent-oölites").[1]

In other cases the substance of the oölitic grains has been completely changed, in some even before final deposition, in others during the diagenesis of the sediment, or still later through metasomatic or katamorphic processes, as in the dolomitic oölites,[2] some siliceous oölites,[3] and the great variety of oölitic iron ores, the interpretation of which, in most instances, is still far from being satisfactory.

[1] C. W. v. Gümbel, *N. Jahrb. für Min.*, etc., 1873, p. 302. The incrustation of air bubbles by calcium carbonate was observed by Knop in the hot springs at Nauheim. Cf. *ibid.*, 1874, p. 285.

[2] Cf., for instance, W. H. Sherzer and A. W. Grabau, "The Monroe Formation of Southern Michigan and Adjoining Regions," *Mich. Geol. and Biol. Surv.*, Publ. 2, 1910, pp. 35–37; T. C. Brown, "Origin of Oölites and the Oölitic Texture in Rocks," *Bull. Geol. Soc. America*, XXV (1914), 759. For European occurrences see the text-books of Zirkel (*Petrography*), Tschermak, etc.

[3] Cf., for instance, the siliceous oölites of Pennsylvania, in Brown, *op. cit.*, pp. 760–68.

See 16 pp. ahead!

RHYTHMIC BANDING OF MANGANESE DIOXIDE IN RHYOLITE TUFF

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The material upon which this study is based was collected by the writer on the south slope of Tumamoc Hill, the largest of a group of low hills of the same name about a mile west of Tucson, Arizona. The Desert Laboratory of the Carnegie Institution of Washington is located on the north slope of this hill. The geology of this region is presented in a paper[1] by C. F. Tolman, Jr.

As the writer had been unable to find any description of a similar occurrence of an eccentrically banded structure of manganese dioxide in rocks, it seemed to him that a description of this occurrence would be of interest. The structure will be referred to as rhythmic banding. This term seems to be the best, as the structure cannot be called an orbicular structure, which it resembles to a certain extent, because that term is applied to certain crystalline aggregates in igneous rocks.

Mode of occurrence.—The specimens of manganese dioxide were found in the talus at the foot of a bed of rhyolite tuff which outcrops on the southern slope of Tumamoc Hill. The tuff, according to Professor F. N. Guild,[2] consists of volcanic ash with numerous inclusions of pumice and darker, more basic, fragments. The volcanic ash consists of glass, fragments of quartz, feldspar, ferromagnesian minerals, and kaolinized material. Professor Guild gives the following analysis:

SiO_2	73.59
Fe_2O_3, Al_2O_3	13.95
C_aO	1.41
MgO	0.75
K_2O, Na_2O	11.23

This analysis shows that the rock is very siliceous.

[1] *Publication No. 113, Carnegie Institution of Washington*, pp. 67–82.

[2] F. N. Guild, *Publication No. 113, Carnegie Institution of Washington*, p. 81, and *American Journal of Science*, XX (1905), 314.

An analysis of the material to determine the percentage of MnO_2 was made by Mrs. W. A. Tarr. It was found that it was merely a stain which was readily removed from the tuff by acids. The amount of MnO_2 present was 0.82 per cent.

At the point where the material was collected the rhyolite tuff is about 100 feet thick. It is overlain by a basalt and rests upon an andesitic conglomerate. As none of the specimens could be located on the face of the bluff it is not known whether the structure formed after the material had accumulated in the talus or while it was still in place. Likewise it cannot be determined from which part of the bed of tuff the material was derived.

Description of the rhythmically banded structure.—The light- to dark-brown color of the rhythmically banded manganese dioxide in the light-gray tuff gives the rock a very striking appearance (Fig. 1). The amount of manganese dioxide in each structure is small (see analysis above), for the tuff is merely colored and is not replaced in any way. This staining process was greatly aided by the very porous character of the material. Practically all the banded areas are circular or elliptical, the former shape predominating, though a few are irregular in outline. In size they vary from 39 mm., as a maximum, down to mere brown specks.

All the structures show either eccentric or concentric banding, this being true of those which are as small as 1 mm. in diameter. The banding is very delicate in most of them and is due to variations in the shade of the brown color. The bands are usually about a fraction of a millimeter in width, but in some of the large structures the bands are as much as 2 mm. in width, and occasionally the central zone has a diameter of 9 mm. and is uniformly tinted throughout (see Fig. 1). There are sometimes ten to fifteen bands in these larger structures. The rings are not absolutely uniform in their spacing or in their intensity, but they are so nearly so that slight variations in the composition of the solutions would account for the differences. The photographs do not show the bands clearly because of the small differences in light values between the zones. (See the drawing, Fig. 2.) The manganese dioxide affects the color of the finer pumiceous material, but as a rule does not change the color of the fragments of quartz, biotite, and other minerals

within the area of the banding. The outer part of the structures is usually darker than the interior.

The remarkable thing about these structures is that in a majority of them the bands are not concentric. In one case the nucleus was

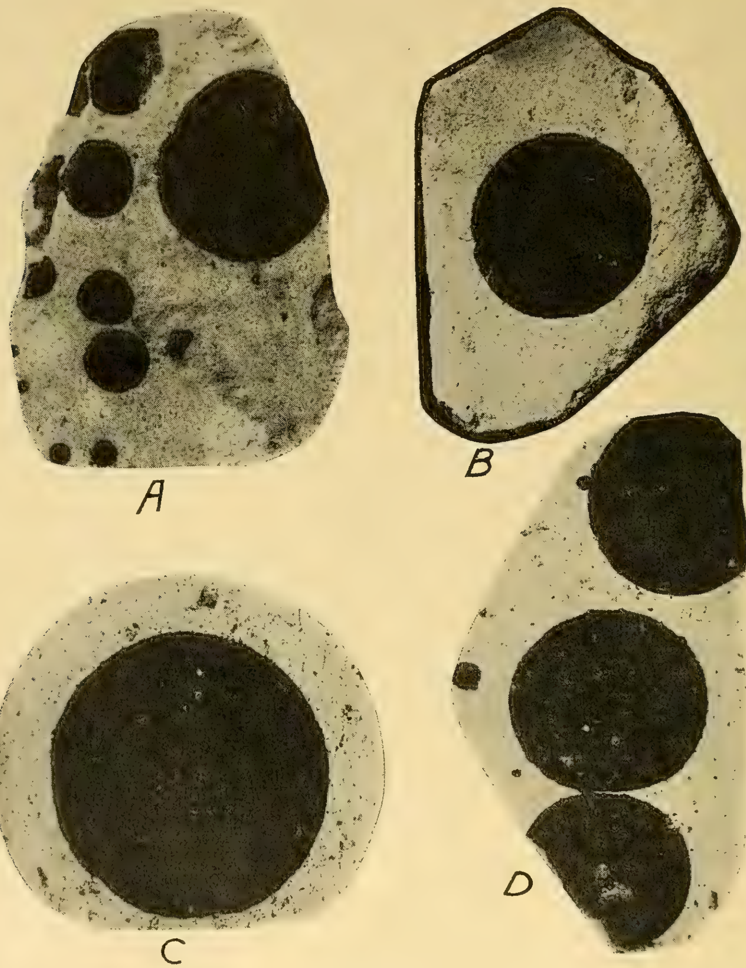

FIG. 1

A, Several spheroids in one piece of tuff
B, Spheroid showing the rings
C, Spheroid somewhat enlarged, showing rings
D, Three eccentric spheroids, slightly enlarged

8 mm. from one side and 20 mm. from the other, yet the structure was spherical. The majority have their nuclei to one side of the true center. It was this peculiar zoning that first attracted the writer's attention.

The only regularity of arrangement of the banded structures in the tuff is their relationship to the surface, as they are more numerous near the exposed surface of the fragments of tuff. All of the specimens on hand show weathered faces on one or more sides, thus indicating that the structures are definitely related to the surface of the talus blocks from which they were obtained. The largest structures are usually an inch or so from the surface, the intervening spaces being filled with numerous smaller banded areas, which not infrequently coalesce. A larger one may partially or wholly envelop a smaller one, apparently without affecting its color in any way. Again, two large ones may be so close that only a line separates them, yet each is distinct, or they may interfere and produce a lobate structure.

Fig. 2.—Tracing of an eccentric structure. Actual size.

A rather striking feature is the position of the nuclei in those forms that are eccentric and that lie near the weathered surface of the talus block. The nuclei are on the side of the structure which is nearest to the weathered surface, and the bands widen upon the opposite side. This may be definitely connected with the origin of the rhythmic banding. The largest structures and also those most nearly circular lie farthest below the surface. These, as a rule, are also the most perfectly banded structures.

Suggestions as to the origin of the rhythmic banding in the manganese dioxide.—The origin of the rhythmic banding is an interesting problem, and the two following suggestions appear to be the most feasible explanations of the phenomena: (1) the manganese was leached out of the tuff and deposited near the surface of the blocks, or (2) some mineral in the tuff furnished the manganese, the dioxide forming in the zone around it.

1. That the aggregation of the manganese into rhythmic zones might be due to the same process that produces the well-known

dark coating called "desert varnish," which is found on surface materials throughout the desert region appears to be plausible. This coating is thought to be due to the evaporation of water drawn from the interior by capillarity, the salts in solution being deposited at the surface. The writer has never been able to find an exact statement of the chemistry of this process, and he feels inclined to doubt the applicability of the method suggested, because iron and manganese salts are very difficult of solution even under favorable conditions, and it is well known that the arid climate of Arizona and New Mexico favors oxidation and tends to inhibit reduction, which is a necessary step in the solution of the salts of these elements.

However, in the case of the tuff the solution could circulate through it readily, as it is very porous, and if proper solvents were present some manganese might be dissolved. Upon evaporation at or near the surface, where oxidizing conditions prevail, the manganese would be thrown down as the oxide. Once started, the structure would grow by fresh additions from the outside. As the solutions were moving outward it is to be expected that the growth on the inside would be most rapid, and thus the eccentric rings would develop. Variations in the amount of manganese and the hydration of the resulting oxide would account for the color variations. At a distance from the surface the structure would be nearly circular, because of the more uniform addition of material.

It should be noted, however, that rhyolites are usually very low in manganese, which is against the theory that the manganese has been derived from the rhyolite tuff. Such rocks nevertheless occasionally contain minerals which are high in manganese, the garnet spessartite being especially common in them. Such a mineral, even though present in small amounts, when broken and scattered through a block of tuff might furnish a fair source of manganese. Likewise biotite sometimes contains manganese, and considerable biotite (nearly always hydro-biotite) occurs in the tuff. These are therefore possible sources of the manganese.

2. The manganese dioxide of the rhythmically banded structures may have originated from and developed around a fragment

of some manganese mineral. No definite evidence of the presence of such a mineral could be found, although one would be supposed to be occupying, or to have occupied, the center of the structures. The original mineral may have been spessartite, which, as has been noted, occurs in rhyolites, as at Rosita Hills, Colorado. It might also have been some manganese-rich ferromagnesian mineral, such as biotite, or one of the pyroxenes or amphiboles.

Water could readily enter the porous tuff and attack the spessartite. The manganese would be taken into solution largely by the water from the immediate rainfall and probably in the form of the carbonate. It could be carried out some distance (about one inch in the larger structures) before deposition ceased. Deposition would be caused by the oxidation of the manganese salt to manganese dioxide, a process that would be favored by the arid climate of the region.

A study of the bands favors the view that they are due to the same process as is the formation of Liesegang's rings, also known as rhythmic banding.[1] Once the manganese is in solution it will diffuse outward through the tuff. Holmes's demonstration that the rings may be produced in loosely packed flowers of sulphur shows that gels are not essential for their development. The porous tuff would be analogous to the flowers of sulphur in permitting the diffusion in this case.

The manganese solution would diffuse outward at a rate dependent upon its concentration. As it mingled with other solutions containing oxygen, the concentration of the respective ions would increase until a labile condition occurred, when precipitation would take place, thus producing a ring. The color of this ring would depend upon the concentration of the solution and in part upon the hydration of the resulting oxide. The manganese solution would then move on (provided its rate of diffusion exceeded that of the other solution) through the zone depleted of oxygen until a second

[1] Recent discussions of rhythmic banding or precipitation are given in the following papers: J. Stansfield, "Retarded Diffusion and Rhythmic Precipitation," *Am. Jour. Sci.*, 4th series, XLIII (1917), 1–26; H. N. Holmes, "Rhythmic Banding," *Science*, New Series, XLVI (1917), 442; J. Stansfield, "Rhythmic Precipitation," *ibid.*, New Series, XLVII (1918), 70.

concentration occurred. As the solutions became weaker the rings would become farther and farther apart unless the concentration of the oxidizing solution became stronger. The width of the zones between the rings would depend upon the relative rates of diffusion of each solution. That there was a slight change in the concentration of the solution as long as there was a source of the manganese is shown by the gradually increasing intensity in color in the outer portions of the structures. The larger fragments of minerals in the tuff are uncolored because of their density.

The eccentric character of the banding is probably the result of several factors. The rate of diffusion of the two solutions was probably different in different directions. The rate of diffusion inward from the surface of the oxidizing solution was probably most rapid, hence the oxidizing solutions met the manganese solutions nearer the nucleus on the side nearest the surface. This interpretation is in accord with the fact that the majority of the structures show wider zones of rings on the side opposite to the surface, where the rate of diffusion of the manganese solutions is greater than that of the oxidizing solutions. Another factor may have been the varying porosity of the tuff, although this is not so likely as the foregoing, because it is not probable that the majority of the banded structures should have the same variation in porosity on the same side. When the blocks of tuff were lying in the proper position downward diffusion as influenced by gravity might aid in producing the eccentric rings. Unlike in laboratory experiments, where the rhythmic banding is produced in a gelatine of uniform composition and density, the rhythmic banding in nature would find varying factors on all sides, hence one should really expect the banded structures to vary from perfect rings. The varying width of the rings themselves is due to the variable character of the solutions. It would seem that this suggestion as to the origin is the better of the two and, if correct, furnishes an interesting example of rhythmic banding in rocks.

Summary.—Rhythmically banded structures of manganese dioxide are found in rhyolite tuff near Tucson, Arizona. These structures are eccentric, which is an unusual mode of occurrence.

They are apparently due either to the manganese being derived from the surrounding tuff and aggregated into the banded forms, precipitation being due to oxidation, or to the mangagese dioxide being derived from a mineral located at the nucleus of the structure and being precipitated in successive rings by rhythmic precipitation following the mingling of the outwardly moving manganese solution with one of oxidizing character. The latter view is believed to be the most probable.

THE RELATION OF THE FORT SCOTT FORMATION TO THE BOONE CHERT IN SOUTHEASTERN KANSAS AND NORTHEASTERN OKLAHOMA[1]

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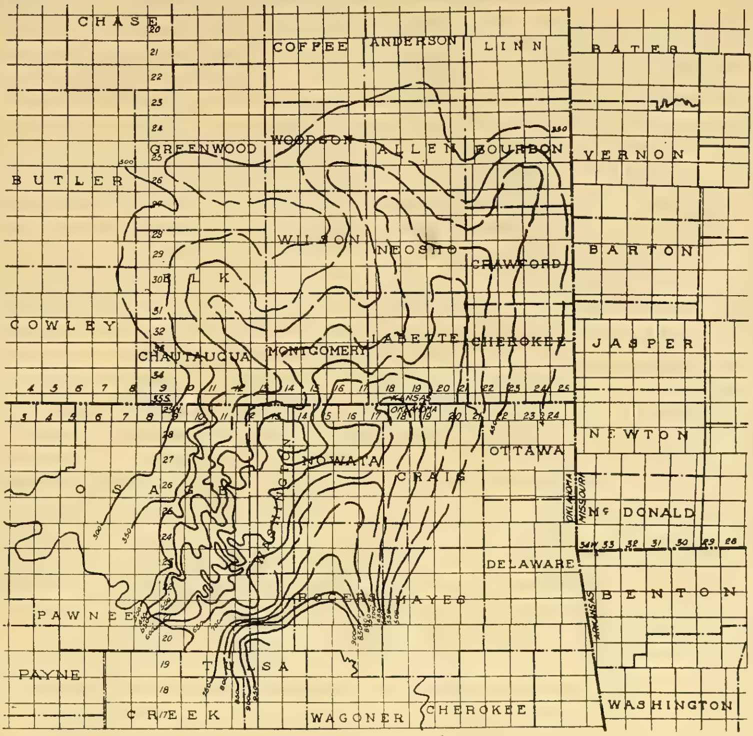
The Fort Scott formation is a limestone with interbedded shales of the lower Pennsylvanian system in southeastern Kansas and northeastern Oklahoma. The outcrop of this formation extends from the region north and east of Fort Scott (T. 25 S., R. 25 E.), Kansas, southwestward to several miles south and east of Broken Arrow (T. 18 N., R. 14 E.), Oklahoma, where it is thin and too much covered for further mapping. The Boone chert (Osage series) of the Mississippian system is a hard, cherty limestone which outcrops in the extreme southeastern part of Kansas and the northeastern corner of Oklahoma. These two limestone horizons dip gently to the west and are separated in this area by the Cherokee formation. The Cherokee formation (Pennsylvanian) consists largely of shale with a few limestone and sandstone beds. Toward the southern edge of the area under discussion other formations appear between the Boone chert and the Fort Scott formation. They are known as the Mayes[2] limestone, the Fayetteville, the Pitkin, and the Morrow formations and consist largely of limestone with some shale. These affect only the area south of the territory discussed.

The map on page 619 shows a number of isobathic lines, or lines connecting points of equal intervals, between the top of the Fort Scott formation and the top of the Boone chert. These intervals were determined from measured geologic sections on the outcrop of the formations and from about five hundred records of wells which have been drilled to the Boone chert, west of the outcrop

[1] Published by permission of the chief geologist, Empire Gas and Fuel Company.

[2] L. C. Snider, *Okla. Geol. Surv. Bulletin No. 24*, p. 27.



CONTOUR MAP
SHOWING INTERVAL BETWEEN FT. SCOTT LIMESTONE and THE BOONE CHERT OF SOUTHEASTERN KANSAS AND NORTHEASTERN OKLAHOMA.

of the Fort Scott limestone. The records have been studied carefully and the top of the Fort Scott limestone determined by means of "spiderweb" cross-sections made from several thousand well records scattered uniformly from the locality of the outcrop on the east, westward past the edge of the area.

The interval between the Boone chert and the Fort Scott limestone, i.e., the thickness of the Cherokee shale and Fort Scott limestones, at their outcrop near Pryor Creek, Oklahoma, has been determined as being 500 feet. This is considerably less than has been given heretofore for this interval, but the measurements have been carefully checked by three parties and the results are in substantial agreement.

From a study of the isobathic lines it will be observed that the greatest intervals recorded between the Fort Scott limestone and the Boone chert are in a northeast-southwest line from Labette County, Kansas, to Rogers County, Oklahoma. The interval becomes smaller both to the east and to the west of this line.

In this connection it is interesting to note that the thickness of the limestone in the Fort Scott formation averages 20 to 40 feet on the outcrop and thickens rapidly westward to an average of 80 to 100 feet in northeastern Osage County, Oklahoma, and southeastern Chautauqua County, Kansas. Thence the formation thins to the west until it can scarcely be recognized in the well logs in west central Osage County, Oklahoma, and western Chautauqua, Elk, and Greenwood counties, Kansas. The alignment of greatest limestone thickness in the Fort Scott formation parallels the northeast-southwest alignment of greatest interval between the Boone chert and the Fort Scott formation.

The greater thickness of the Cherokee shale along the line from Labette County, Kansas, to Rogers County, Oklahoma, as shown by the isobathic lines, is interpreted as indicating the deeper part of the depositional basin in which the Cherokee was deposited. The lowest beds in this portion of the basin do not appear to have been deposited in the areas to the east and west, which were probably either land or covered intermittently by shallow water. It is only in this deeper part of the basin that we have the thick, lenticular sands, such as the Bartlesville, Burgess, and Tucker, which are

so productive of oil and gas, in northeastern Oklahoma and southeastern Kansas. These sands are present in the lower one-third of the Cherokee formation and are practically confined to the area inclosed within the 400-foot isobathic line.[1] The sands higher in the section extend farther to the west. The lenticular nature of the sands in the lower part of the formation indicates an oscillating sea, and the occurrence of the greatest limestone thickness of the Fort Scott formation, to the west of the deepest part of the Cherokee basin, indicates a shifting of the basin in that direction as the Cherokee time interval progressed.

Irregularities appear in the isobathic lines, as in northern Chautauqua County, Kansas, for example. These irregularities appear to be due to the presence of troughs during the early history of the basin. These troughs may have been caused by erosion of the Boone chert before the deposition of the Cherokee shales or may have been formed by downwarping during the deposition. The trough mentioned is shown as a flat on the Boone chert contour map of the Kansas Geological Survey.[2]

Many smaller irregularities appear on the southwestern side of the basin, indicating that the surface of the Boone chert was considerably eroded by the time the Pennsylvanian sea encroached upon the land to the west. This is well shown by the isobathic lines in Washington and Osage counties, Oklahoma. In several places the presence of old river valleys may be indicated by the successive curving in of the isobathic lines, such as the one extending from the north edge of T. 23 N., R. 12 E. to T. 25 N., R. 10 E., Osage County, Oklahoma.

The writer is indebted to Mr. A. W. McCoy, under whose direction the work has been carried on, and also to Dr. L. C. Snider, for valuable suggestions.

[1] The productive sands in the fields farther west, which have generally been correlated with the Bartlesville sand, are considered from our studies to be at other horizons.

[2] *State Geol. Surv. of Kansas, Bulletin No. 3*, p. 197.

A FORM OF MULTIPLE ROCK DIAGRAMS

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A number of suggestions have been made for rock diagrams, designed to show the variation in several constituents through a series of rocks, and a modification is here offered of a method proposed by Adams.[1] He used the chemical analysis directly. This gave a conspicuous line for silica in nearly every analysis. It occurred to the writer that the relative proportions of constituents could be seen more clearly if the analyses were recalculated to the norms,[2] in which a larger number of constituents are usually present in notable amounts. Since the mode sometimes differs from the norm, this method is of course subject to any criticism of the norm as a method of stating rock composition; but it has some advantage over the simple plotting of chemical constituents. Furthermore, the method applies to the mode almost as well as to the norm. Those who do not like the norm can measure or calculate the mode, but in this case relatively few constituents ordinarily attain prominence. It will be recalled that a single feldspar in the mode may be three in the norm, and that certain ferromagnesian minerals in the mode may be divided in the norm.

As a further modification of Adams' method the writer finds it desirable not to plaster the individual rock diagrams together, but to clamp them into position leaving them free for rearrangement, as they are studied from various points of view. Thus in a gabbro (see "A Type of Igneous Differentiation," p. 627) it was of interest to arrange the rocks in what might be called stratigraphic position to see if the magnetite showed a tendency to concentrate at any special horizon; while in the study of differentiation it was

[1] F. D. Adams, "A Graphical Method of Representing the Chemical Relations of a Petrographic Province," *Jour. Geol.*, XXII, 689.

[2] Whitman Cross, J. P. Iddings, L. V. Pirsson, and H. S. Washington, *Quantitative Classification of Igneous Rocks*. University of Chicago Press, 1903.

of interest to try first an arrangement in the order of increasing albite, and then in the order of increasing anorthite, and so on. The sequence and the exceptional rocks are noted in the process of arrangement even more readily than in the photographs.

Attention may be called to certain significant points shown by the diagrams (Figs. 1, 2, and 3). Norms were selected at random

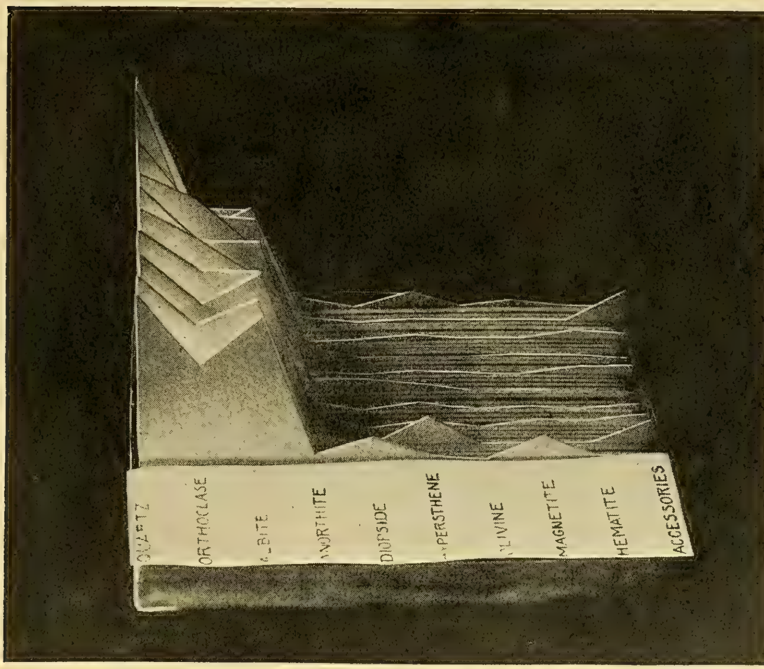

FIG. 1.—A multiple diagram of a series of rocks from the Alaskose subrang in the quantitative classification. The predominance of quartz and alkali feldspars is clear.

in the subrangs in the quantitative system. The contrast in the three pictures is evident; so also is the relative uniformity in the norms of a single picture. A further remark is to be made in this regard, however. The uniformity is clear in the first two but not so clear in the third. This group of rocks is from the class of salfemanes; that is, salic and femic minerals are present in about equal amounts. Salfemanes are grouped according to the relations

of salic minerals, as far as the classification is commonly used. In the subrang Auvergnose the diagram shows that the prominent femic mineral may be either diopside, hypersthene, or olivine. For this reason the diagrams of salfemane subrangs may show a great deal of variation in the femic minerals. However, if the

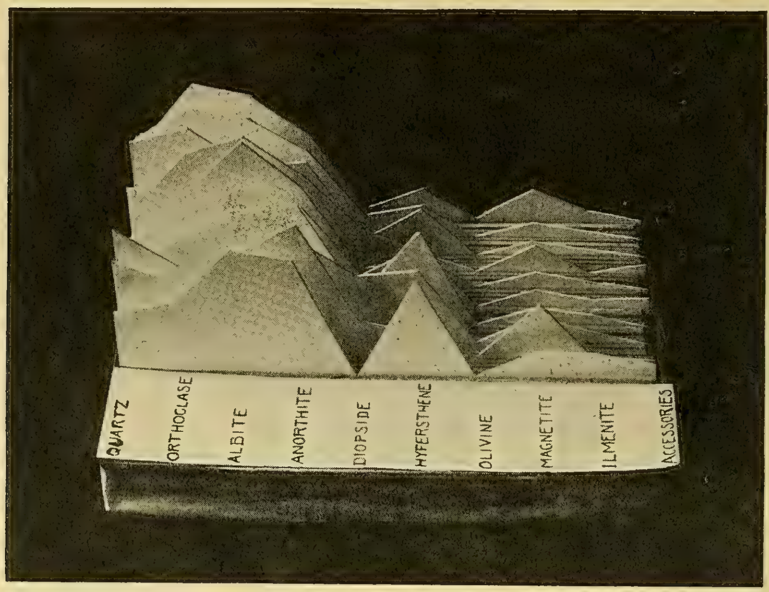

Fig. 2.—A multiple diagram of a series of rocks from the Harzose subrang in the quantitative classification. The quartz and feldspars are predominant here also, but the more siliceous minerals here give way to increased amounts of anorthite.

classification is carried one step farther, to the "grad," these varying rocks would fall in different grads. As a whole it is clear that analyses of a single group in the quantitative classification show their relationship conspicuously in the diagram.

Attention may also be called to the contrasting series shown in the diagrams of "A Type of Igneous Differentiation." The variation in the gabbro series at Duluth shows no tendency to develop a type intermediate between the gabbro and the red rock. The second picture, the red rock, seems to be a strikingly different class of rocks.

ON OÖLITES AND SPHERULITES[1]

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COLLOID-CHEMICAL INTERPRETATION OF ORIGIN OF OÖLITES

Schade's work.—The most important contribution toward a satisfactory interpretation of the origin of oölites and related structures was made by a member of the medical faculty of the University of Kiel, H. Schade, in 1909 and 1910, in his papers on the origin of urinary calculi and on the formation of concrements.[2] In these he demonstrated experimentally that concretionary bodies form when a substance passes from the state of an emulsion colloid (or "emulsoid") to that of a solid, and that if the change leads to the crystalline state the resulting structure is radial if the substance is pure; if, however, other substances, colloid or crystalloid, are precipitated along with it a concentric structure is developed. Corresponding with this law, natural holesterin gallstones, when 80 to 90 per cent pure, show a radial crystalline structure, while gallstones containing 25 per cent or less holesterin exhibit perfect concentric lamination.

Observations on iron chloride.—A substance which lends itself well to a demonstration of the process involved, because it requires no special preparation, is the commercial hydrated iron chloride. A

[1] A rock is called "oölitic," or an "oölite," if it contains or consists of small grains or units of dominantly concentric structure. A rock is called "spherulitic" (but not a spherulite) if it contains or consists of small grains or units of dominantly radial crystalline structure. An individual grain of a spherulitic rock is called a "spherulite." For an individual grain of an oölite the term "ovulite" might be used, which appears to be preferable to Kalkowsky's "oöid" not only for symmetry's sake. In this paper the term "spherite" will be used for all grains of the same origin irrespective of their structure.

[2] Heinrich Schade, "Zur Entstehung der Harnsteine und ähnlicher konzentrisch geschichteter Steine organischen und anorganischen Ursprungs," *Zeitschr. für Chemie und Industrie der Kolloide*, IV (1909), 175–80; "Ueber Konkrementbildungen beim Vorgang der tropfigen Entmischung von Emulsionskolloiden," *Kolloidchemische Beihefte*, I (1910), 375–90.

concentrated solution of this salt, as was noted accidentally, exhibits all the characteristics of an emulsion colloid; for instance, a noticeable change of viscosity with change in temperature, stability in the presence of salts with polyvalent ions, etc. When dried at ordinary room temperatures, large spherocrystals are formed, perfectly spherical in shape when formed freely suspended in the heavy liquid, hemispherical in shape when formed in contact with the walls of the vessel or with the surface of the liquid. So far I did not succeed in preparing thin sections of these bodies, owing to the low melting-point of the salt (42° C.). In very thin layers, however, spread out on a slide, the growth is seen to take place in one plane only, yielding layers thin enough for optical study. This, combined with a macroscopic observation of the bases of the hemispheres, gave the following results:

Spherites formed relatively rapidly during normal evaporation appeared structureless on cross-section with the center distinctly darker but not sharply separated from the rest. In other cases there was a sharply defined light center, and sometimes an outer lighter layer, distinct from the rest. Some spherites seemed to have formed through the union of several macroscopic drops, judging from an indistinct pattern shown in cross-section. When formed on a slide, growing in one plane only, they always exhibited a radial crystalline structure, the individual fibers being visible under the microscope. Superimposed on this radial structure there appeared in some of the spherites, on the same slide with the others, concentric lines outlining separate crystalline layers, which, however, all consisted of the same material.

Spherites formed during extremely slow evaporation (due to a crust formed on the liquid) showed a concentric structure of delicate layers of different color, especially in their outer part, representing in every respect true oölites. In several cases ten and more layers were counted in a radius of 2 mm.

These experiments illustrate well the principles of Schade: (1) the spherical shape of spherites is due to the tendency of the droplets, forming during the separation of the dispersed phase of an emulsoid, to coalesce;[1] (2) the difference between spherites of

[1] The solid crust which, in some experiments, formed on the viscous liquid containing the growing spherites was, in every case, ruptured upon further loss of water,

radial and concentric structure depends on the amount of other substance thrown out simultaneously with, and mechanically enmeshed in, the growing structure.

Ordinary concretions seem to differ only in size and, in many cases, in an excess of mechanically enmeshed materials. That these principles underlie the formation of most, if not all, sedimentary oölites, spherulites, and concretions is rendered probable by the fact that almost all substances which are known in one of these forms are also known in the others and are the same that are known to occur extensively in nature in the colloidal state. A brief review will emphasize this relation.

Review of natural oölites.—1. Silica: Des Cloizeaux found spherulites of clear silica in a jelly-like paste.[2] Spherulitic hyalite was observed by Jimbo from the Etchu province of Japan,[3] and similar hyalites with concentric structure from hot springs in the Ugo province were described by Takimoto.[4] Silica plays the rôle of the "binding" colloid in most pisolites and is an important constituent of most iron hydroxide oölites. Siliceous concretions are of wide occurrence. Silicic acid is the standard inorganic emulsoid sol of the laboratories.

2. Water: Among the hailstones we find all transitions between typical spherulites and spherites of concentric structure.[5] That

and from the opening extensive *botryoidal surfaces* grew up, leaving cavities underneath the crust. Iron chloride, therefore, offers a complete analogy to all the common forms of natural gels, especially such as have a tendency to grow crystalline *in statu nascendi,* as, for instance, chalcedony. Cf. F. Cornu and H. Leitmeier, "Ueber, analoge Beziehungen zwischen den Mineralien der Opal-, Chalcedon-, der Stilpnosiderit-, Haematit- und Psilomelanreihe," *Zeitschr. für Chemie und Industrie der Kolloide,* IV (1909), 285–90.

[2] F. Roth, *Allgemeine und chemische Geologie,* I (1897), 591, Anm.

[3] K. Jimbo, "The Siliceous Oölite of Tateyama, Etchu Province," *Beitr. z. Min. Japans, Tokio,* 1905, pp. 11–75 (quoted from abstract in *Zeitschr. für Chemie und Industrie der Kolloide,* IV [1909], 287).

[4] T. Takimoto, "The Siliceous Oölite of Sankyo, Ugo Province," *Beitr. z. Min. Japans,* 2 (1906), 60–61 (quoted from *Neues Jahrb. für Min.,* etc., I [1907] 197).

[5] According to Schade the coarse layers overlapping onion fashion, frequently met with in hailstones, are not equivalent to the exceedingly delicate lamination of true oölites, but are due to plastic deformation under external pressure. See Schade, *Kolloidchemische Beihefte,* I (1910), 388; "Ueber die Koëxistenz des kristallinischen und kolloiden Zustandes," *op. cit.,* pp. 389 ff.

water vapor in the atmosphere frequently has the properties of an emulsion colloid is well known.

3. Hydroxides: The hydroxides of iron, manganese, and aluminum occur in all three forms with the exception of the last named, which is, as far as I know, not found in spherulitic or analogous structures. Aluminum hydroxide has, however, little chance to occur in the pure state. "Meta-"hydroxides in concentrated solution are known to be in the emulsoid state[1] and are widely distributed in that form in nature.

4. Phosphates: Phosphatic oölites are common in our western phosphate beds. Concretions are widespread and some show radial crystalline structure. The colloid origin of certain phosphates has long been recognized.[2] Because of the emulsoid character of their sols the phosphates are classed with the "gelatinous salts."[1]

5. Barite: Oölites consisting largely of barite with small amounts of gypsum and selenite were described by Wuestner[3] and Moore[4] from oil wells in Hardin County, Texas. They are of special interest because at least some of them undoubtedly formed in the wells after they were equipped, since they are found inside the tubing in sizes which could never have passed through the small mesh of the screen.[5] As the oil in the well has a temperature of 125° F. and contains free sulphuric acid, they offer a good example of an unquestionable case of an inorganic production of oölites. Fortunately some of these oölites, as shown on the micrographs of Wuestner's paper, Figs. 2–4, exhibit the same pattern of tubes radiating from the center which is so frequently seen in sections of sedimentary calcareous oölites[6] and which Kalkowsky, in his

[1] Ostwald Wolfgang, *Handbook of Colloid-Chemistry*, translated by Martin H. Fischer (Philadelphia, 1915), p. 51.

[2] A. F. Rogers, "A Review of the Amorphous Minerals," *Jour. Geol.*, XXV (1917), 530–33.

[3] H. Wuestner, "Pisolitic Barite," *Jour. Cincinnati Soc. Nat. Hist.*, XX (1906), 245–50, 4 figs.

[4] E. S. Moore, "Oölitic and Pisolitic Barite from the Saratoga Oil Field, Texas," *Bull. Geol. Soc. America*, XXV (1914), 77–79.

[5] E. S. Moore, "Additional note on 'The Oölitic and Pisolitic Barite from the Saratoga Oil Field, Texas,'" *Science*, N.S., XLVI (1917), 342.

[6] For instance, in the oölites of the St. Louis limestone. They are also seen in two sections of bladderstones in the author's possession.

beautifully illustrated paper on the oölites of the Buntsandstein of northern Germany,[1] used as arguments in favor of an organic origin. The formation of the (unstable) barium sulphate sol in this case is possibly analogous to its formation in glycerin, as described by Recoura.[2] Barite concretions are locally found in shales.[3]

6. Calcium carbonate: In the sedimentary oölites we have all transitions from spherulitic to concentric structure. Perfect spheres of calcium carbonate, measuring 1 cm. and more in diameter, with excellent radial crystalline structure were described by the author from Miocene limestones of the Rhine valley.[4] Calcareous concretions are very common. In Drew's experiments, in which he proved the precipitation of calcium carbonate from sea water by *Bacterium calcis*, the first turbidity appearing in his solutions was caused by particles of such fine grain that they could be centrifuged only with difficulty. This suggests a colloid state. In the same experiments small spherulites were formed.[5] Vaughan allowed bottles containing Bahaman shoal-water muds strained through bolting cloth of fine mesh to stand over three months, after which he found in them numerous oölite grains which had grown to such sizes as to preclude their passing through the mesh of the bolting cloth.[6] The gel of calcium carbonate resulting from the precipitation of calcium carbonate from a solution of water-soluble calcium salts and its tendency to form spherulites have long been known. Owing to the elaborate studies of Buetschli, calcium carbonate is perhaps the best known of the "gelatinous salts."[7]

[1] E. Kalkowsky, "Oölith und Stromatolith im norddeutschen Buntsandstein," *Monatsber. d. Deutsch. geol. Ges.*, LX, Part I (1908), 68–125, especially p. 122.

[2] M. A. Recoura, "Sur le sulfate de baryum colloïdal," *Compt. Rend.*, CXLVI (1908), 1274–76.

[3] See, for instance, J. P. Rowe, "Nodular Barite and Selenite Crystals of Montana," *Am. Geologist*, XXXIII (1904), 198–99; for a case in which the primary origin of these concretions is obvious see W. H. Bucher, "Beitrag zur geologischen und palaeontologischen Kenntnis des jüngeren Tertiärs der Rheinpfalz," *Geognostische Jahreshefte*, XXVI (1913), 31.

[4] Bucher, *op. cit.*, p. 80.

[5] G. H. Drew, "On the Precipitation of Calcium Carbonate in the Sea by Marine Bacteria," etc., *Carnegie Publication No. 182* (Washington, 1914), pp. 30–31.

[6] T. W. Vaughan, "Preliminary Remarks on the Geology of the Bahamas," etc. *Carnegie Publication No. 182* (Washington, 1914), pp. 51–53.

[7] Q. Buetschli, *Abh. Goettinger Akad.*, N.S., IV, 1908.

7. Siderite: Siderite is occasionally found in spherulitic form in cavities of basalt (spherosiderite).[1] Dana, Naumann-Zirkel, and others mention the existence of oölitic siderite. The only description of such an occurrence that has come to my attention is that of a specimen described by Dewalque from the Belgian coal measures.[2] Sideritic concretions ("clay ironstone") are commonly associated with caustobioliths.

This association is significant, since a colloid form of siderite was described by Van Bemmelen from the upland bogs of the Dutch province Drenthe, where it is found in the form of concretionary masses in irregular distribution in the peat.[3]

North of Preston, in Bath County, Kentucky, the Devonian limestone, which normally is dolomitic and more or less cherty, is partly replaced by a siderite. A specimen of the ore, presented to me by Dr. A. M. Miller, shows numerous small oölitic grains (0.5 mm. in diameter) of a light green silicate, uniformly distributed through the dark brown rock, which, under the microscope, exhibit a delicate concentric structure, rather indistinct in some grains (Figs. 1 and 2). The surrounding groundmass offers the usual appearance of interlocking siderite crystals. But at the contact with the oölites the siderite crystals show the sharp outlines of perfect rhombohedrons extending into the body of the oölites without disturbing their concentric structure. In this remarkable case the silicate oölites apparently formed in free suspension in a matrix which must have been an amorphous mud or a gel of iron carbonate, which later crystallized out before the oölites had lost their gelatinous character.

The necessary reducing conditions under which this local deposit originated within the coral-bearing dolomites of the Onondaga Sea may have existed in a depression on the bottom of the shallow sea in which the water lay stagnant,[4] or in a lagoon, which would not seem improbable if the assumption of a large island or peninsula

[1] As, for instance, at Steinheim, Hessia, where the author had occasion to observe and collect it.

[2] G. Dewalque, *Ann. d. l. Soc. géol. d. Belg.*, XV, Bulletin (1888), p. lxxx.

[3] J. M. Van Bemmelen, *Zeitschr. für anorg. Chemie*, XXII (1899), 313.

[4] See, for instance, J. Murray and J. Hjort, *The Depths of the Ocean* (London, 1912), p. 257.

in the Onondaga Sea, just to the northwest of this locality, is correct.[1]

These observations render it probable that other sedimentary siderite deposits, especially such as are closely associated with

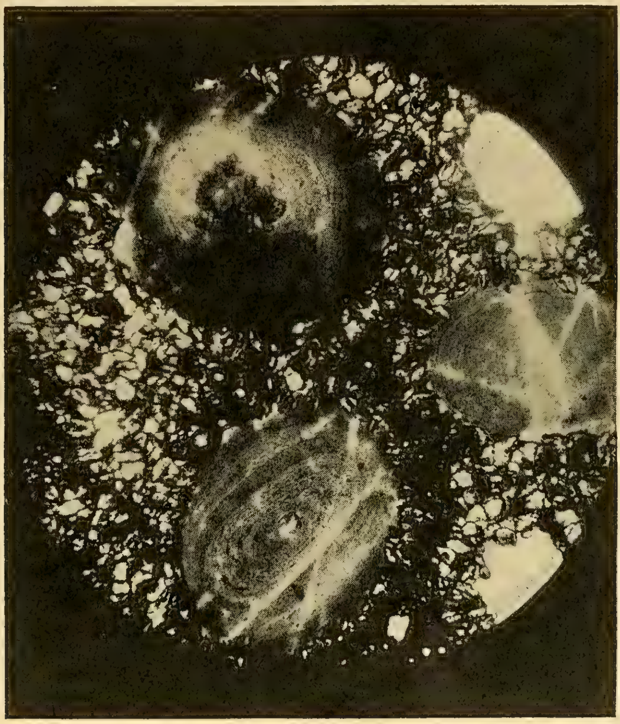

FIG. 1.—Photomicrograph of oölitic grains of a light green silicate in a groundmass of siderite and (secondary) iron hydroxide, forming a local facies of the Onondaga limestone near Preston, Bath County, Kentucky. Note the free edges of the siderite crystals extending into the oölitic grains, cutting through their structure, mostly without disturbing it; also the discordance between outline and structure of the grain near the lower margin. (The longest diameter of this grain measures 0.7 mm.)

caustobioliths (black shales, coal, etc.), first separated out in the colloidal form and subsequently assumed crystalline character.

[1] C. R. Stauffer, "The Middle Devonian of Ohio," *Geol. Surv. of Ohio*, 4th Ser., Bulletin 10, 1909, Pl. 14; C. Schuchert, *A Text-Book of Geology*, Part II (New York, 1915), Pl. 15B; C. Butts, "Geology and Mineral Resources of Jefferson County, Kentucky," *Kentucky Geol. Surv.*, Ser. 4, Vol. III, Part II, Fig. 3.

8. Silicates: Some hydrous iron silicates, as, for instance, the greenalite of the Lake Superior region, and hydrous iron-aluminum silicates, as, for instance, the chamosite of the Jurassic "Minette" ores of Europe and the similar silicates of our Silurian ores, occur extensively in the oölitic form. They show all characteristics of original gels. In the case of greenalite the tendency to aggregate into numerous spherical grains was evident in the experiment.[1] Distinct oölitic structure is also seen in a specimen of fire clay, from the base of the Pottsville from an unknown locality in eastern Kentucky, which was presented to me by Dr. A. M. Miller. A similar occurrence was described by Dr. W. A. Tarr at the last meeting of the Geological Society of America. For the present the question must remain undecided if in these oölitic clays the binding substance is silica or a silicate.[2]

9. Iron disulphide: Only one case of an oölite has come to my attention in the formation of which pyrite seems to have had an independent part; that is, in which it is more than merely a mechanically enmeshed constituent or of secondary origin. In the upper Lias of Northwestern Germany there occur beds which consist partly of massive pyrite cementing the shells of belemnites and ammonites, and partly of nearly black limestone rich in pyrite, the two phases grading one into the other. In the black limestones oölites are found of a deep black color, measuring 0.5–3.0 mm. in diameter, and consisting of sharply defined alternating layers ("shells") of yellow pyrite and black calcium carbonate (soluble in cold HCl with effervescence).[3] Spherical nodules of pyrite with a fibrous radiated structure are not uncommonly found in shales,[4] and ordinary concretions are common. Recently a

[1] C. R. Van Hise and C. K. Leith, "The Geology of the Lake Superior Region," *U.S. Geol. Surv. Mon.*, LII (1911), 522–25.

[2] Cf. Rogers, *op. cit.*, p. 535 ("imperfect pisolitic structure" in a clay consisting largely of the amorphous equivalent of crystalline kaolinite). A fire-clay containing small rounded bodies which are nearly pure alumina was described by Greaves-Walker in *Trans. Amer. Ceram. Soc.*, VIII, 297; quoted from Ries, "Clays" (New York, 1914), 52–53.

[3] T. Brandes, "Die faziellen Verhätnisse des Lias zwischen Harz und Egge Gebirge," etc., *N. Jahrb. für Min.*, etc., Beil. Bd., XXXIV (1912), 391.

[4] For a good example see, for instance, E. M. Nörregaard, *Meddelelser fra Dansk Geol. Fören*, XI (1906), 105.

black amorphous form of iron disulphide was described by Doss, who called it Melnikowite.[1] It is found in the form of small lenses and occasional thin incrustations of Pelecypod shells in gray clays of Miocene age and especially in solid layers of a pyritic sandstone. These consist of a mixture of pyrite and of this amorphous iron

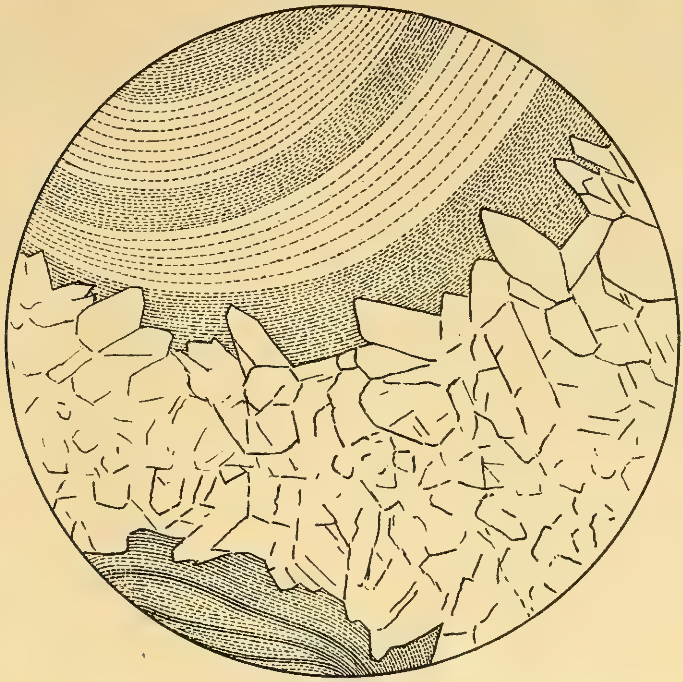

FIG. 2.—Sketch showing the free ends of the siderite crystals extending into oölitic grains. From the same slide as the preceding figure. The large, nearly perfect crystal at the contact in the lower right-hand quadrant measures 0.08 mm. in length.

NOTE.—Owing to the extreme softness of the silicate, A. C. McFarlan, one of my students, who prepared this and numerous other slides for me, was unable to avoid scratches on the oölitic grains. I am also under obligations to P. Scherrer for valuable assistance in the making of microphotographs.

disulphide and contain abundant sand grains which, however, are everywhere seen to be suspended in the groundmass of disulphide. This must, obviously, have been in the state of an amorphous

[1] B. Doss, "Ueber die Natur und Zusammensetzung des in miocaenen Tonen des Gouv. Samara auftretenden Schwefeleisens," *N. Jahrb. für Min.*, etc., Beil. Bd., XXXIII (1912), 662–713.

precipitate or of a gel at the time when the sand grains were dropped into it. The pyrite, which forms part of the layers, must therefore represent the final crystalline product of a series of transformations starting, according to Doss's interpretation, with the gel of hydrated iron monosulphide (FeSH.OH). This assumption is based on the experiments of Feld, who demonstrated that the iron monosulphide, which results from the action of hydrogen sulphide on iron salts, is changed within a few days into amorphous iron disulphide, when hydrogen sulphide is allowed to pass through it in the presence of free sulphur and a reducing agent[1] (conditions realized in the natural sapropels).

In these experiments the precipitate of the monosulphide was of black color and voluminous. In changing into the disulphide it turned brown and settled into a compact mass on the bottom of the vessel, sharply separated from the liquid above and undisturbed by the bubbles of hydrogen sulphide passing through it; it also formed a "mirror" of metallic brown color on the vertical walls of the vessel.[2]

This sudden change in the physical properties of the precipitate of the monoxide, the sol of which is a typical suspensoid, certainly justifies the suspicion that the iron disulphide formed a gel, passing through an emulsoid state.

It should be emphasized that any one of the substances referred to above may be present in an oölitic grain as the binding colloid or as an accidentally enmeshed crystalloid. The latter case is illustrated by many of the numerous organic oölitic structures, like animal and vegetal pearls, gallstones, urinary calculi, and many other similar bodies occasionally found in the tissues of the animal body, in which the percentage of organic substance, in those cases the binding colloid, is often very small.

SIGNIFICANCE OF THIS INTERPRETATION

This brief survey justifies the assumption that most, if not all, oölitic and spherulitic grains were formed by at least one constituent substance changing from the emulsoid state to that of a

[1] W. Feld, *Zeitschr. für angew. Chemie*, XXIV (1911), 97–103.

[2] Feld, *op. cit.*, p. 101.

solid; that the spherical shape of the grains is due to the tendency of the droplets forming during this process of separation to coalesce; and that the difference between radial and concentric structure depends on the amount of other substance thrown out simultaneously with and mechanically enmeshed in the growing structure.

The chief value, at present, of this interpretation of the origin of oölites to the geologist lies in the fact that it gives a new direction to future work. The questions to be answered in each case are:

1. What factors determined the colloid dispersion of the salt and what was the medium of dispersion?

2. What caused the separation of the colloid from the dispersion medium?

3. What made possible the suspension of the growing spherite?

The chemical geologist will have to decide in each case whether the factors involved in the first two questions were physical (for instance, the presence of protective colloids) or chemical (for instance, the nature and quantity of other substances in solution) or biological (for instance, the action of bacteria).

INTERPRETATION APPLIED TO SEDIMENTARY OÖLITES

Shape of grains due to growth in suspension.—The last question, on the other hand, is of special interest to the stratigrapher. We were accustomed to think that calcareous or limonitic oölites owe their spherical shape to constant rolling on the sea (or lake) bottom. While it cannot be said that such an origin is impossible, there is experimental evidence which raises doubts in my mind as to whether agitation of the suspension or dispersion medium would ever allow of the formation of such structures. Besides, there are now very few cases left in which such an interpretation might seem necessary.

The alternating layers of silica and of carbonate of the pisolites form while the spherites are being carried up by the current of the flowing spring water. The layers of hailstones form as they fall. Limonitic oölites form in the gels of organic iron salts on the bottom of Swedish and Finnish lakes.[1] Oölites of bauxite and of limonite

[1] For references see F. Beyschlag, J. H. L. Vogt, and P. Krusch, *The Deposits of the Useful Minerals and Rocks*, translated by S. J. Truscott (London, 1916), II, 982.

form in residual clays.[1] The calcareous oölites of Great Salt Lake form suspended in the jelly-like masses of algae, as was described by Rothpletz.[2] Drew's artificial oölites formed in the agar-agar of his bacterial culture, and in Vaughan's experiments they grew in the soft amorphous calcareous muds which occur so abundantly on the shores of the Bahama Islands.

Apparent exceptions.—I know of only two cases which at first sight at least seem to form exceptions to the rule that oölites grow in free suspension.

1. Gaub, in a splendid paper, described oölites containing numerous microscopic shells of a Foraminifer classed with the Miliolidae (*Ophthalmidium ooliticum*).[3] These he considers to have been incrusting forms which attached themselves to small fragments of shells, crinoid stems, etc. (now forming the nucleus of the oölitic grains), and, being rolled about in the amorphous calcareous mud, held it mechanically and perhaps even localized its precipitation. The fact that a very similar, not incrusting, species of the same genus *Ophthalmidium* is very abundant in the same layers suggests the possibility that these minute shells were only mechanically inclosed in the growing oölite and that surface tension may be responsible for their tangential arrangement. Schade observed, for instance, that in some pearl-like gallstones the holesterin crystals were all arranged tangentially, enmeshed in the binding colloid.[4] Some of the shells within the oölitic grains are flattened on the side facing the center of the oölitic grain. Others, however, exhibit similar deficiencies on the outer side. Gaub interpreted the former as evidence of attachment, the latter as evidence of mechanical wear. They may, however, both be due to a small amount of solution during the growth of the oölite.

[1] C. K. Leith and W. J. Mead, *Metamorphic Geology* (New York, 1915), pp. 35–37; for literature on European "bean ores" see Beyschlag, Vogt, and Krusch, *op. cit.*, p. 990.

[2] A. Rothpletz, "On the Formation of Oölite," *Amer. Geologist*, X (1892), 279–82 (translated from *Botanisches Centralblatt*, LI [1892], 265–68).

[3] F. Gaub, "Die jurassischen Oolite der Schwaebischen Alb," *Geol. und palaeont. Abh.*, N.S., IX (1910), Heft 1. An earlier shorter paper, *N. Jahrb. für Min.*, etc., Part II, (1908), pp. 87–96, Pls. 7–8.

[4] Schade, *Kolloidchemische Beihefte*, I (1910) 385.

Since, at present, the original papers are inaccessible to me I cannot judge the degree of probability of this suggestion. It is, of course, possible that frequent interruptions in the normal process of growth of the oölitic grains, caused by a stirring of the calcareous muds during storms, permitted the *Ophthalmidia* to attach themselves to the grains and thereby to participate in their growth.

2. The second case comprises oölites in the formation of which filamentous algae are supposed to have had an active part. Such oölites were, for instance, recently described by Van Tuyl from the Ordovician of Iowa.[1] They contain in abundance "minute sinuous fibers similar to those which characterize the Girvanella type of calcareous algae." In oölites from the shores of the Red Sea, Rothpletz found "peculiar vermiform, and not rarely dichotomously branching, canals that are filled up with calcite."[2] In fresh-water springs and pools threadlike Schizophyceae are usually found associated in great numbers with the primitive types which cause the separation of the lime carbonate. Rothpletz, therefore, considered the vermiform structures of the oölites as "threadlike algae which were, of course, not themselves immediately concerned in the oölite formation, but by the company in which they lived were imprisoned with it." Since Van Tuyl states expressly that his oölites showed in addition to the supposed calcareous algae "good concentric and radial structure," there can be little doubt but that Rothpletz' interpretation may be applied to them directly. Similar canals might, however, also be produced by boring algae or fungi, the ramified canals of which are found permeating larger shells and pebbles as well as shells of Foraminifera in size comparable to the oölites.[3]

Relation of algae to oölites.—The rôle which Rothpletz assigned to such Schizophyceae as Glœocapsa and Glœothece in the formation

[1] F. M. Van Tuyl, *Science*, N.S., XLIII (1916), 171; *Jour. Geol.*, XXIV (1916), 792–97.

[2] Rothpletz, *Am. Geologist*, X, 280.

[3] J. E. Duerden, "Boring Algae as Agents in the Disintegration of Corals," *Bull. Amer. Mus. Nat. Hist.*, XVI (1902), 323–24. They were also described from Ordovician Foraminifera and from numerous Siluric fossils (see F. B. Loomis, "Siluric Fungi from Western New York," *Bull. N.Y. State Mus.*, VIII (1900), No. 39, 223–26, especially Fig. 3 on Pl. 16).

of oölites appears to have been generally misunderstood. The cells of these primitive algae correspond in size to the largei forms of bacteria.[1] Bodies resulting from the precipitation of lime on or in the thick, jelly-like membrane surrounding the minute cells would therefore have a diameter fifty to a hundred times smaller than that of the oölites. Such bodies were, in fact, observed by Rothpletz in the oölites from Great Salt Lake as well as in those from the Red Sea, and were found to be mechanically incased in the oölites like the filamentous algae. "In quite delicate sections the calcareous substance [of the oölites] . . . . is interrupted by scattered, minute granules. If we dissolve the section cautiously and slowly in very dilute acid, the granules remain behind exactly in their original position, and we recognize in them the dead and crumpled Glœocapsa cells" (p. 280).

From this it follows that if the Schizophyceae have at all an active part in the formation of oölites[2] it must be similar to that played by the closely related bacteria which separate calcium carbonate in the form of an emulsoid sol from solutions of calcium salts and thereby create conditions favorable for the growth of oölitic grains.[3]

The papers in which Wethered described Girvanella from many oölitic rocks of various ages[4] are, unfortunately, not accessible to me. The structure of certain calcareous oölites described by him, according to Rothpletz, seems "to have great resemblance to that of the Sinai oölite and is, perhaps, to be explained in the same manner." Others, however, judging from one of his figures reproduced in Harker's *Petrology for Students*,[5] represent true incrusta-

[1] Glœocapsa: 2 μ in diameter; Glœothece: 4–5 μ long; Anthrax bacillus: 6 μ long.

[2] Weighty reasons against this assumption were adduced by T. C. Brown, "Origin of Oölites and the Oölitic Texture in Rocks," *Bull. Geol. Soc. America*, XXV (1914), 754–57.

[3] As this process is probably due to a reaction of the calcium salts of the water with an alkaline excretion of the algae, we cannot, in this case, speak of "lime secreting" algae (cf. W. Pfeffer, *The Physiology of Plants*, I, translated by Ewart [Oxford, 1900], 133). Compare Drew's account of the action of denitrifying bacteria (*Carnegie Institution of Washington*, *Publication No. 182*, p. 30).

[4] E. Wethered, "On the Occurrence of the Genus Girvanella in Oölitic Rocks," etc., *Quar. Jour. Geol. Soc.*, XLVI (1890), 270–83; LI (1895), 196–206.

[5] Fourth ed., London, 1908, fig. 69, p. 261.

tions of organic fragments by the interlacing tubes of Girvanella and should therefore not be called oölites at all.[1] When exposed, true oölites may, of course, be incrusted in the same way.

SOURCES OF ERROR IN INTERPRETING ORIGIN OF OÖLITES

Secondarily deposited oölites.—Erroneous conceptions concerning the origin of oölites may arise if no clear distinction is made between layers in which the oölitic grains are found *in situ* and such in which they were redeposited after transportation. The secondary origin of oölitic deposits may be recognized by the practical absence of a matrix, by the uniformity of size of grains (indicating sorting), by cross-bedding, or by the presence of substances accidentally enmeshed in the oölitic grains which are foreign to the surrounding matrix, etc. In such cases the oölitic grains were either washed by waves or currents from their place of origin and redeposited in water, or they were carried inland by the wind where they may have formed dunes, as they do now on the shores of the Red Sea and of Great Salt Lake.[2] The recognition of such secondary oölites and their correlation with synchronous primary deposits may, under some circumstances, convey valuable information to the paleogeographer.

It is often quite difficult to prove satisfactorily the origin *in situ* of an oölite. For this we must, in many cases, rely entirely on a microscopic study of the relation existing between the matrix and the oölitic grains. In some cases, however, the characteristic incrustations and massive growths, called "stromatoliths" by Kalkowsky,[3] are found associated with the oölitic grains and by their presence prove the primary nature of the oölites, as, for instance, in the Upper Triassic (Rhaetic) of England, the Mississippian of Belgium, the Lower Bunter of Northwestern Germany, the Tertiary of the Rhine Valley, etc.[4]

[1] The term "pseudoölite" has been used for grains imitating oölites; for instance, minute pellets of dense limestone in a limestone matrix (cf. O. M. Reis, *Geognostische Jahreshefte*, XXII [1909], 228).

[2] J. Walther, *Lithogenesis der Gegenwart* (Jena, 1894), pp. 659, 699, 849; A. W. Grabau, *Principles of Stratigraphy* (New York, 1913), pp. 468, 472.

[3] Kalkowsky, *Monatsber. Deutsch. geol. Ges.*, LX, I (1908), 68–125.

[4] Cf. O. Reis, "Ueber Stromatolith und Oolith," *N. Jahrb. für Min.*, etc. (1908) Part II, pp. 114–38.

Under the microscope these stromatoliths exhibit a structure of delicate layers identical with that of the oölites, with which they are often connected by all stages of transition.[1] They differ greatly, both in structure and in origin, from the coarse calcareous crusts which are formed by thick, felted masses of fresh-water algae and mosses on shells and pebbles.[2] The two can easily be distinguished when found associated in the same formation, as, for instance, in the Miocene limestones of the Rhine valley.[3]

The stromatoliths are the sedimentary equivalent of the calcareous and siliceous "sinter" of the hot springs; stromatolithic crusts of limonite are commonly found in lake and bog ores.

In the simple experiments with iron chloride, described in the first part of this paper, similar growths were observed in the same cases in which spherites with oölitic structure were produced. In these experiments flat expansions formed below the massive crust which sealed the liquid, and, to a smaller degree, also at the bottom of the vessel, corresponding in thickness to the radius of the oölitic grains and showing the same delicate concentric structure. There can be little doubt but that they represent the experimental reproduction of stromatoliths.

Subsequent alteration of oölites.—Another, more fundamental, source of error in the interpretation of the origin of oölites has been the more or less altered condition of most fossil oölites. Many calcareous oölites, for instance, have suffered complete recrystallization which, starting usually in the center of the grains,[4] replaces their original structure by a few crystals, or even a single large calcite individual, concentrating all impurities in a thin layer at their periphery. Such extreme cases have been inter-

[1] Cf., e.g., Bucher, *Geogn. Jahresh.*, XXVI (1913), 78–79, and Pl. I, Fig. 22.

[2] Cf., e.g., J. M. Clarke, "The Water Biscuit of Squaw Island, Canandaigua Lake, N.Y.," *Bull. N.Y. State Mus.*, VIII (1900), No. 39, 195; W. Schmidle, "Postglaciale Ablagerungen im nordwestl. Bodenseegebiet," *N. Jahrb. für Min.*, etc. (1910), Part II, 105–22.

[3] Bucher, *op. cit.*, pp. 80–81.

[4] Cf. the illustrations and the discussion of the mechanism of this process in Reis, *Geogn. Jahresh.*, XXII (1909), 227–31, and Pl. 11, Figs. 25–30.

In summary the method shows the composition of a series of rocks, with the following advantages. There are no excessive peaks except in case of some rare monomineralic rocks. The diagram can be based on either norm or mode. The cards can be rearranged for the study of each mineral, or the geographic or "stratigraphic"

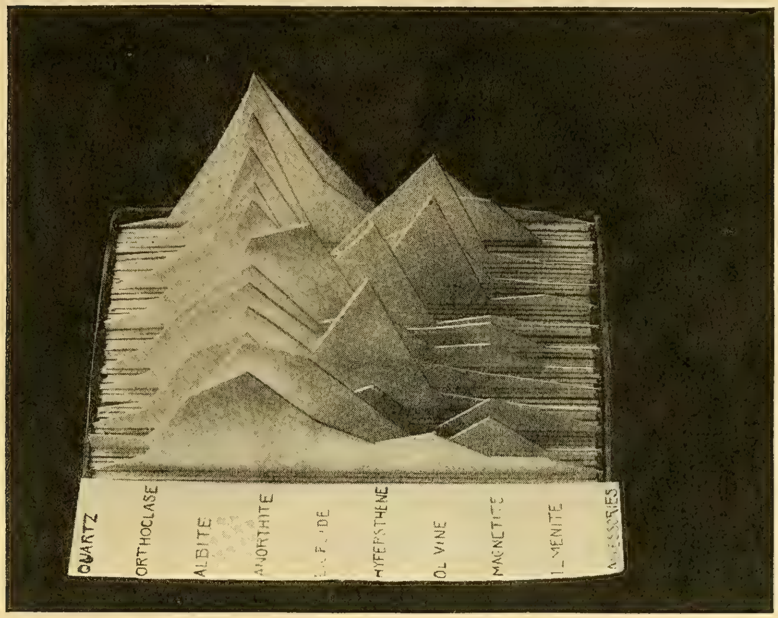

FIG. 3.—A multiple diagram of a series of rocks from the Auvergnose subrang of the quantitative classification. Quartz is negligible and anorthite is prominent. The femic constituents are prominent in this figure but are not uniform. One rock shows abundant diopside, one hypersthene, one olivine.

position of the rocks. Certain features of the norm classification are easily visualized by the diagram.

GEOLOGICAL LABORATORIES
UNIVERSITY OF MINNESOTA
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A TYPE OF IGNEOUS DIFFERENTIATION[1]

FRANK F. GROUT
University of Minnesota

CONTENTS

INTRODUCTION

This paper begins with a summary description of the rock types of the Duluth gabbro formation, and suggests the processes by which they formed. Since there are similar rock series in other districts, where the relations of large intrusions are not so clear, or where the study has been less detailed, it is suggested that the same processes are indicated in those districts. This type of differentiation, therefore, is not at all unique.

[1] Published by permission of the Directors of the Minnesota Geological and Natural History Survey and the United States Geological Survey. Part of a dissertation presented at Yale University.

THE ROCKS OF DULUTH

The Duluth gabbro and its differentiates are intrusive into Middle Keweenawan flows, probably at a considerable depth. At Duluth it is evident that a feldspathic gabbro was intruded and cooled before the main mass of more basic gabbro was intruded. The mass is so large that it must have required thousands of years to cool, plenty of time for its differentiation into the many types now found. Some differentiates assume an intrusive relation to those earlier to crystallize, the most conspicuous case being the intrusion of "red rock," or granophyr, into gabbro. When studied in detail the mass shows by the intimacy of the geologic connection that, with all its variety, it is essentially a single geologic unit. Not only is the red rock related to the gabbro by association and intermediate phases, but over most of the area the two portions of the gabbro cannot be distinguished. Even at Duluth the two masses are not everywhere distinguishable. The averages differ only about 10 per cent in the amount of feldspar. It is believed that no great error will be introduced if the whole mass of data on the Duluth gabbro is considered as a unit. The main gabbro at Duluth and in many other outcrops is conspicuously banded.[1] The form has been named a lopolith[2] (Fig. 1).

The descriptive petrography of the formation need not be rewritten here in detail.[3] However, this study adds a few points from the type locality, where the exposures are exceptionally clear. The new data also make it possible to present a consistent, though not at all final, summary of the petrography of the whole mass.

THE GABBRO

The diagrams of the modes from measurements (Fig. 2) and the norms from analyses (Figs. 3 and 4) show the variation in the two gabbro masses at Duluth, without regard to position in the mass. It is evident that no simple linear series could be arranged on the

[1] Frank F. Grout, "Internal Structures of Igneous Rocks," *Jour. Geol.*, XXVI (1918), 439.

[2] Frank F. Grout, "The Lopolith," *Am. Jour. Science*, XLVI (1918), 516.

[3] The references and a correlation of the varying nomenclature are given by A. N. Winchell in *U.S. Geol. Sur. Mon. 52*, pp. 395–407.

basis of mineral composition. The main gabbro types shown in the diagram, even those of extreme composition, occur as alternating bands.

The average gabbro is gray when fresh and weathers nearly white. The texture is medium to coarse, granitoid to ophitic (see Fig. 5). The order of crystallization is in most cases plagioclase, olivine, magnetite, and augite. Olivine is not conspicuous in the

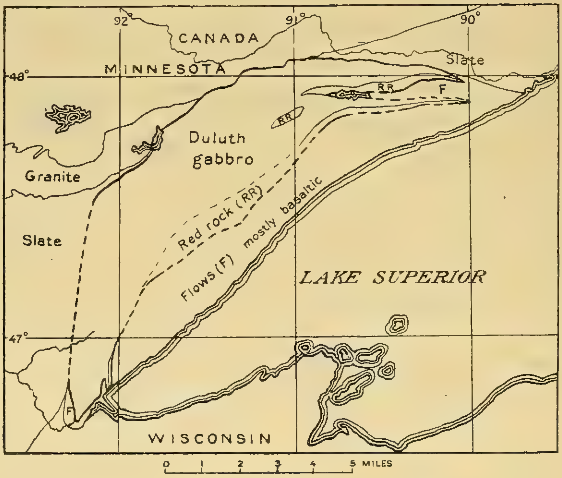

FIG. 1.—Sketch map of the Duluth gabbro area

average gabbro except on the weathered surface, where, being highly ferruginous, it turns to a bright brown, contrasting with the darker augite and iron ores. There is very little alteration. The character of the main minerals is surprisingly constant from end to end of the series of outcrops. All the olivine has about 30 per cent FeO whether in peridotite or anorthosite. There are few outcrops in which the feldspar differs much from Ab_1An_2. The pyroxene, with few exceptions, is augite low in lime.

The rocks of the gabbro series may be classified as normal gabbro, olivine gabbro (and the corresponding diabase, Fig. 5), troctolite, peridotite, magnetite gabbro, and anorthosite. Several specimens might show some further variation, but their occurrence is local and there is no evident importance in the distinction. The

pegmatitic phases have been discussed elsewhere.[1] The analyses tabulated below show the composition of the abundant types.

Peridotite phase.—Bands of peridotite occur in the banded gabbro a few yards above the base. The large bands are over

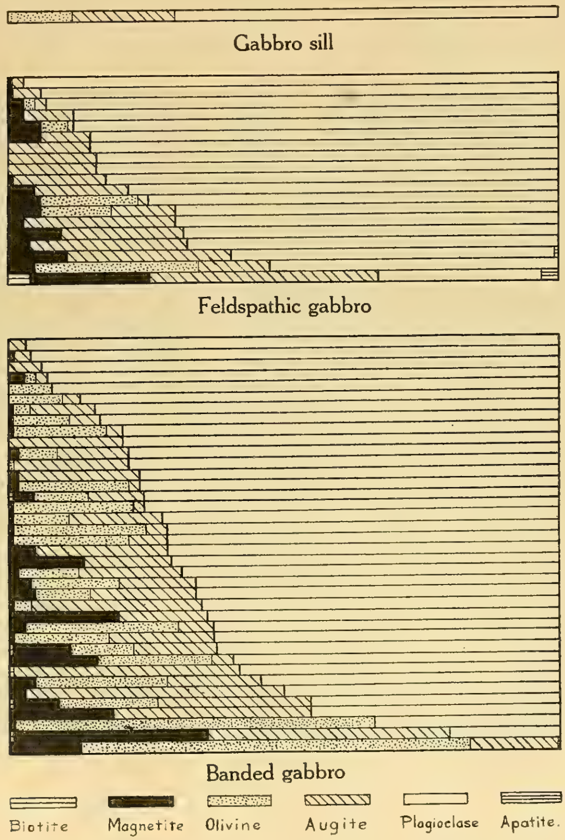

FIG. 2.—Diagram of measured modes of Duluth gabbro

15 feet thick and somewhat variable. They are nearly black, weathering rapidly to a crumbling brown soil. Analysis number 2 in Table I shows the chemical composition, and the diagram (Fig. 2) indicates the mineral composition.

[1] Frank F. Grout, "The Pegmatites of the Duluth Gabbro," *Econ. Geol.*, XIII (1918), 185.

Troctolite phase.—Troctolite, rich in olivine, like that described by Winchell,[1] occurs from the center to the base of the mass, in scattered bands. See analysis number 6 in the table. The proportion of olivine to plagioclase in the several troctolites varies widely, so that the rocks approach peridotite on one side and anorthosite on the other.

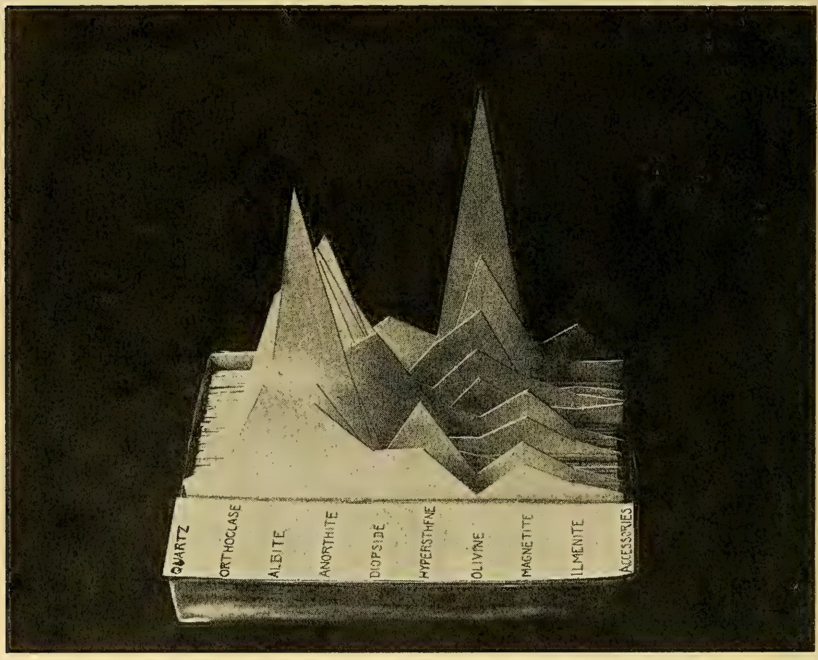

Fig. 3.—Diagram of the norms of analyses of gabbro at Duluth. Many phases have not yet been analyzed.

Anorthosite phase.—At Duluth the early feldspathic gabbro probably contains over 80 per cent plagioclase. Large parts of it by a slight process of differentiation become anorthosite. Analysis 3 of the table is a fair sample, but large masses are even purer feldspar. The later more basic gabbro has less anorthosite, but thin bands of it are not at all rare. An outcrop in Sec. 26, T. 50 N., R. 15 W., resembles the famous anorthosite inclusions in diabase

[1] A. N. Winchell, "Gabbroid Rocks of Minnesota," *Am. Geol.*, XXVI, 281–85.

sills along the shore of Lake Superior. The rock is a conspicuously spotted one (Fig. 6). The darker spots are large poikilitic olivine grains inclosing plagioclase and the white ground mass is feldspar with only a small trace of magnetite. Unfortunately the boundaries of this spotted rock are concealed.

Magnetite phase.—It is possible to find specimens and thin bands of gabbro near Duluth bearing as much as 36 per cent of titaniferous

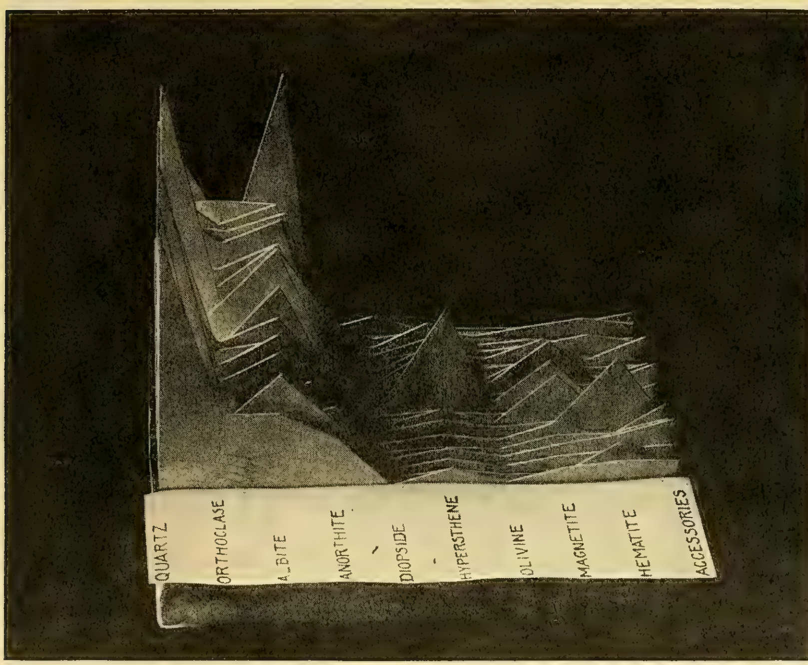

Fig. 4.—Diagram of the norms of analyses of red rock of the Duluth gabbro formation.

magnetite. The bands are near the center of the gabbro, which is nearly three miles thick. There is no olivine in the magnetite rock, but augite is more abundant than in the average gabbro. The band shows fluxion structure, but the minerals seem to have crystallized about simultaneously, magnetite late in some (Fig. 5). Similar bands in Cook County, one hundred miles northeast, much larger and richer in magnetite, make up the titaniferous iron ores for which the gabbro is famous.

THE RED ROCK

Introduction.—The "red rock" has purposely been left out of the discussion of variations from the gabbro, not because it differs from the gabbro more radically than anorthosite differs from peridotite, but because its geologic relations are very different. It has not been seen as bands in banded gabbro. The change from gabbro to red rock is somewhat abrupt and without alternation. The gray gabbro rapidly gives place to a bright red rock very different from the gabbro in mineral, chemical, and physical characters.

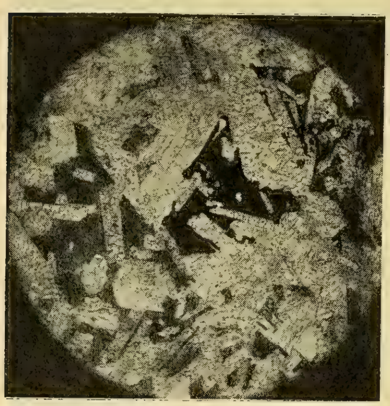

FIG. 5.—Thin section of Duluth gabbro showing diabasic texture. White to light gray, basic labradorite; dark gray, augite; black, magnetite which is late to crystallize. Plain light, $\times 20$.

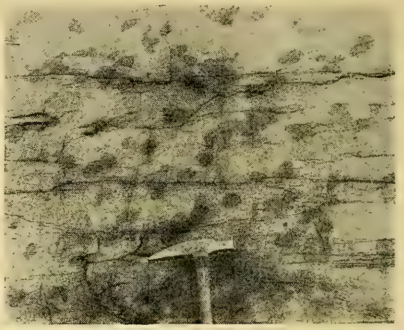

FIG. 6.—Spotted anorthosite. The dark areas are olivine crystals, which poikilitically inclose thousands of smaller plagioclase grains.

The "red rock" has become widely known under this name because of its brilliant color and the difficulty of giving it a more accurate classification. Some confusion may arise also from the fact that red felsitic flows appear in the Keweenawan series. The rock here discussed is intrusive and granitoid.

The chief outcrops near Duluth are irregular patches at the top of the main gabbro and apophyses into its roof; it occurs also near the top of the earlier feldspathic gabbro, in a large sill close above the gabbro, and in some small dikes near the bottom of the gabbro.

Description.—The texture varies from sugary near contacts to very coarse in certain patches. The rock is peculiarly friable, so that

hand specimens can hardly be trimmed from it. A striking local variation contains long needles of dark minerals in a red matrix. In thin sections it is micropegmatitic, varying to granitoid in some large masses. Miarolitic cavities are numerous in some places. Variability is as characteristic of the minerals as of the textures. The chief red mineral is a feldspar stained with considerable hematite and badly kaolinized. Probably most red rock contains two feldspars; zoning is especially common in the phases grading into the gabbro. Quartz, though abundant, is rarely visible except with the microscope as an intergrowth. Hornblende is the chief ferromagnesian mineral, but it is fibrous and mixed with secondary minerals as if itself secondary. Biotite is rare and in most cases secondary.

A sample of the red rock was selected from the type locality for analysis (number 25 of the table), and while it cannot fully represent so variable a rock, it shows some features in common with earlier analysis also quoted in the table. Nearly all the norms include corundum; many also include hematite. For a rock consisting largely of graphic intergrowth of quartz and feldspar—supposed eutectic proportions—the quartz is high and alkalies are low. The lime and potash, both being low, make the rock resemble bostonite in composition, but it is more quartzose than that type. Winchell[1] has tabulated the terms used in the common qualitative system for the red rocks. Possibly granophyr is appropriate for most of the rock.

Gradation and relations.—In the sill in the eastern part of the city there is a remarkable example of perfect gradation from diabase to red rock. The diabase is of ordinary type, with a finer contact phase at the base. It is exposed almost continuously for a width of a mile, equivalent to a thickness of several hundred feet. The diabase grades up into a red-rock zone of smaller thickness and less regularity, though a belt may be followed several blocks. It is noteworthy that while the sill must be nearly 1,500 feet thick, the conspicuous gradation zone is less than 50 feet, from black diabase to intensely red granophyr.

[1] A. N. Winchell, "Review of Nomenclature of Keweenawan Igneous Rocks," *Jour. Geol.*, XVI (1908), 765–74.

A somewhat different gradation is observed in Lincoln Park and near the top of the inclined railroad to Duluth Heights. In these places it is possible to select samples showing all stages between gabbro and red rock, but the relations are not those of a regular zone. The upper part of the banded gabbro shows many local patches with interstitial red granophyr, grading into dikelike stringers and patches of red rock of complex form and relations (Fig. 7). Many of these stringers with sharply defined walls can be traced along their length into less sharply defined markings and finally grade imperceptibly into the black gabbro which formed the walls a few feet away. Both the gabbro and the red rock intrude the roof, sometimes in the same crack, sometimes more distinctly. Although a considerable part of the red rock is so much later in time of solidification that it could intrude the gabbro, the texture of the red rock is coarse up to its contacts and grades into that of the gabbro without a break, indicating that they were about equally hot. The irregularity in the form of the stringers may also be a sign that the gabbro was not wholly solid (see Fig. 7). Such a relation may be properly described as that of an aplite.

Similar relations of gabbro to red rock, both gradational and aplitic, are easily traced for many miles along the belt at the northeast end of the gabbro in Cook County, where the combined thickness is so reduced as to make the mass more like a sill, and the red rock constitutes a larger proportion of the intrusion than at Duluth. The same relation may be expected in the central, thicker part of the gabbro mass,[1] but this has not been mapped in detail as yet (see Fig. 1).

A third gradation from red rock to gabbro is that in the pegmatites near the base.[2]

Origin of the red rock.—All three of these occurrences of red rock and gradations would seem from field studies to be clearly attributable to a differentiation. However, this sweeping assignment of the granophyr to differentiation ignores a whole group of occurrences

[1] This is not wholly in agreement with the brief statements in *U.S. Geol. Sur. Mon. 52*, pp. 374–75.

[2] Frank F. Grout, "The Pegmatites of the Duluth Gabbro," *Econ. Geol.*, XIII, (1918), 185.

which are characteristic of the contacts of diabase with acid rocks. The association is too striking to be thus ignored. At Duluth the case is illustrated by a very narrow granophyr zone at the base of an extrusive diabase north of Short Line Park, where it overflowed a quartzose sand. Where such flows rest on the other flows no

FIG. 7.—Aplitic stringers of red rock in the Duluth gabbro, near the top

such granophyr has been detected. Again, at Pigeon Point a gabbro seemingly related to the Duluth gabbro has inclusions of quartzite which are characterized by a complete inclosing shell of red rock.[1] The composition of the red rock in these cases is not such as can be derived from the sediment, nor from the average

[1] W. S. Bayley, "The Rocks of Pigeon Point," *U.S. Geol. Surv. Bull. 109*, p. 101; R. A. Daly, "The Geology of Pigeon Point," *Am. Jour. Sci.*, XLIII, 423.

magma, nor any possible mixture. Mr. T. M. Broderick, of Minnesota, has recently checked up the previous work on the chemical nature of the rocks by determining the alkali content of all the rocks at the contact of gabbro with an inclusion of quartzite. If red rock in this situation is derived from quartzite it is derived from the immediately adjacent inclusion. The gabbro has 3.49 per cent alkali and the quartzite 3.60 per cent, but the red rock has more than either, 8.33 per cent. Some differentiation must have occurred in this case, and probably in all similar contacts, many of which have been listed by Bowen.[1]

If it is granted that differentiation occurred, it is easily shown that local assimilation has been relatively slight. The composition of any known differentiate would become evidently hybrid with small additions of the sediments near by.

Deep-seated assimilation and differentiation—syntexis—may have occurred, but there is little evidence that it played much part in forming red rock. There are several examples of assimilation in the gabbro. The quartz gabbro described by Winchell[2] is near an inclusion of quartzite. Similar endomorphic contact effects are exposed in other parts of the gabbro. None of the assimilation phases resembles red rock.

It is therefore maintained that the granites associated with the Duluth gabbro were dependent more on differentiation than on assimilation of acid rocks. The general discussion of the processes by which granites separate from gabbro magma would be mostly theoretical and too long for this paper, but one theory has been forced into prominence by local observations on the gabbro. The several occurrences may all be explained by supposing that the original magma contained some vapors under pressure and that these tended to separate and escape from the main magma, bearing with them those acid, alkaline constituents for which they seem to have a special affinity. The accumulation of a definite upper zone of red rock would then be the result of a quiet rise of the lighter vaporous separate under an impervious roof. The aplitic areas near the top would be similar gravitative separates, disturbed by

[1] N. L. Bowen, "The Gowanda Lake District, Ontario," *Jour. Geol.*, XVIII, 658.

[2] A. N. Winchell, "The Gabbroid Rocks of Minnesota," *Am. Geol.*, XXVI, 348.

some movements at about the time of solidification. The pegmatites and aplites below would be located not so much by gravity as by simple vaporous tension; the lighter separate, being more fluid, might penetrate cracks on any side of the magma chamber in advance of the main magma. The red rock at the borders of siliceous sediments and filling the pores of sandstones as a cement may similarly have escaped from the magma under the tension of the vapors. The position of such a red-rock zone may be determined less by gravity than by porosity. The vaporous solution could escape through the pores in advance of the gabbro. In an extreme case this separation of red rock might even be determined by a porous inclusion. However, the most favorable conditions for the accumulation of red rock must be the combination of a large body of magma with plenty of water and a sandstone roof having a tight cover above.

RELATION OF ROCK TYPES TO POSITION

It is estimated that over two-thirds of the gabbro mass at Duluth consists of olivine gabbro, varying only slightly from the average. Such average rocks are scattered from top to bottom. On the other hand, specialized types have a more limited range. The peridotite occurs only near the base; the magnetite gabbro, equally heavy, is near the center; the anorthite ranges from the center toward the top and is largely in the thin earlier intrusion. Very locally at the base of the early gabbro there is an apatitic hypersthene gabbro. The occurrence of red rock, mostly near the top and in a sill at a higher horizon, is emphasized above.

DIFFERENTIATION

Introduction.—It must be granted, in regard to the Duluth lopolith, that a magma supply was available, and, as indicated by the earlier flows in the same region, it varied from time to time or place to place. The problem of its history as a lopolith begins with its intrusion into the present chamber. Various theories are current as to the processes by which a magma during such a history gives rise to a series of rock types instead of a single one. The roof of the magma for much of its area was diabase and too much like the

magma to indicate that assimilation after intrusion could yield new types. Successive intrusions certainly differed slightly, and it is likely that some parts of the earlier magma were very nearly of the composition of anorthosite. However, although this early magma is different from the later, larger intrusion, there is no sign that the variety in the main gabbro is due to successive intrusions. If this main gabbro was heterogeneous when intruded there was plenty of time for it to become mixed, unless the tendency of the parts was to become more distinct rather than to mix. It therefore seems that the main development of variety in the lopolith depended on processes of differentiation. The variety of rocks described above shows how thorough this differentiation was.

Processes of differentiation.—Recent experimental work is very conclusive in maintaining the reality of crystal settling in a magma and the improbability of extended diffusion as factors in differentiation. It is much less conclusive in dismissing convection and assimilation and the separation of immiscible fractions of magmas.[1] There are some evidences at Duluth which indicate the processes involved.

Crystal settling versus convection.—One of the first considerations in a study of crystal settling concerns the plagioclase. The mass was so large that at Duluth the crystals must have grown very slowly, for the most part too slowly to yield zoned structures. With such very slow cooling a plagioclase would begin to crystallize with a composition much more basic than would be calculated from an average of the magma; but as crystallization proceeded it might have readjusted itself to the magma, so changed in composition as finally to be the plagioclase indicated by the composition of the average magma. This adjustment is supposedly interfered with in cases of very slow cooling, hence to be expected at Duluth, by the settling or floating of the early basic crystals out of reach of the residual liquid. The crystals should then be more basic plagioclase wherever the early crystals accumulated and more acid elsewhere.[2] Let us see how the Duluth gabbro fits the case.

[1] N. L. Bowen, "Later Stages in the Evolution of Igneous Rocks," *Jour. Geol.*, XXIII (1915), supplement to the December number.

[2] F. L. Bowen, *ibid.*, p. 33.

Nearly all the feldspar of the gabbro, through a thickness of three miles, is basic labradorite or acid bytownite, with surprisingly little variation and no apparent relation between position and the slight variations found. Near the top for a few feet the feldspars are zoned, and directly above is the red rock in small amount. Can 15,000 feet of bytownite, Ab_1An_2, settle out of a magma of more acid composition without changing the composition of the residual liquor, so as to produce a notable change in the crystals forming? And, if so, can 15,000 feet of bytownite, Ab_1An_2, settle from a mother liquor that amounts to less than 300 feet of acid andesine? It is evidently absurd to think that the main gabbro settled, leaving a mother liquor of red rock in such small amount. The gabbro feldspars are too uniform. The early crystals, which were very basic according to theory, forming from a labradorite melt, must have remained in contact with the mother liquor until equilibrium was established and they became average in composition. The crystals may have settled a little, but the viscous magma more than likely moved with them in convection most of the way. The end of crystallization came when the crystals lodged in the more viscous wall or floor, and there slowly, maintaining equilibrium, the crystals adjusted their composition to that of the magma around them, some bytownite, some labradorite.[1]

In connection with crystal settling the gravitative position of differentiates is cited as strong confirmation. The Duluth gabbro is supposed to be one of the best illustrations, since it is commonly thought that magnetite separated at the base. As a fact, the segregated ores are far from the base; the best concentrations are bands centrally placed in banded gabbro. Ores near the base are contact ores or xenoliths, and the gabbro at the base shows very

[1] The mechanics of the convection has been outlined elsewhere. See Frank F. Grout, "Two-Phase Convection in Igneous Magmas," *Jour. Geol.*, XXVI (1918), 481.

Another more general criticism of crystal settling may be noted at this time. Bowen records in the *Am. Jour. Sci.*, XXXIX, 175, that crystals grow during settling in a crucible from an infinitesimal start to one-tenth of a millimeter, in settling 15 millimeters. How far-fetched it is then to think of the grains of common igneous rocks as having settled thousands of feet in a laccolith or batholith! Crystal settling is an idea to think of in terms of a few feet rather than in hundreds of feet.

little enrichment in magnetite.[1] Weinschenk is authority for the statement that this is a general rule in the segregation of magnetite.[2]

Fig. 8 shows the specific gravities of the rocks of which there are data in their "stratigraphic" sequence. A curve has been drawn to indicate in a greatly generalized way the decrease in

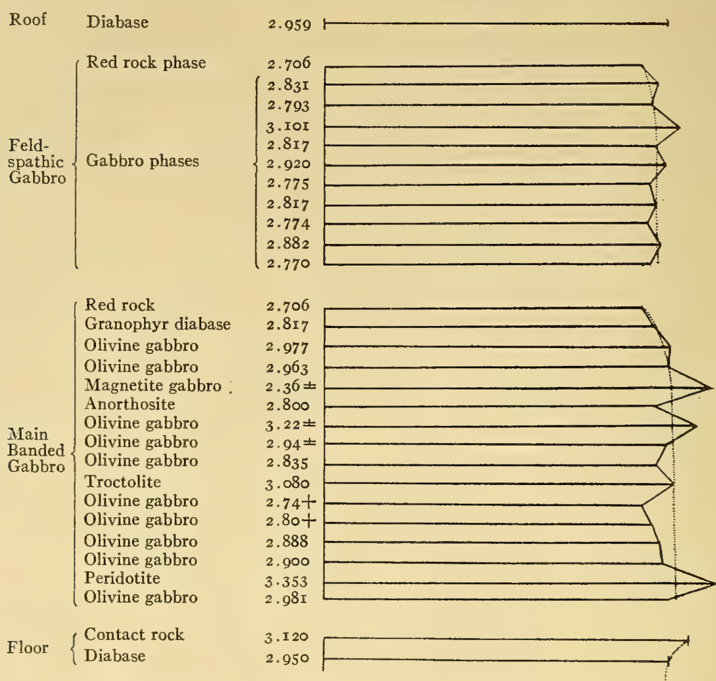

FIG. 8.—Specific gravities of Duluth rocks in "stratigraphic" order

specific gravity toward the top of the mass at Duluth, but when the data are studied in detail it is found that the curve is hardly justified. One of the heaviest rocks found was well above the center. It is thought that many of the cited examples of gravitative arrangement will show in detail the same erratic curve.

How is this irregular specific-gravity series explained? The idea of crystal settling has not been so stated as to cover it. The

[1] T. M. Broderick, "The Relation of the Titaniferous Magnetites of Northeastern Minnesota to the Duluth Gabbro," *Econ. Geol.*, XII (1917), 663.

[2] Dr. E. Weinschenk, translation by A. Johannsen, "The Fundamental Principles of Petrology." McGraw-Hill Co. (1916), p. 45.

idea of convection with a rhythm of crystallization would lead one to expect exactly what is here found.[1] The first crystals to form, if not altogether too light, would be the first to drag along the bottom. The heavy minerals would take their turn, and the magnetite being, at least partly, later in time of crystallization would remain liquid until the lower parts of the chamber were filled with layers of rock. Thus both the uniform feldspar and the curve of gravity may be taken as signs of convection.

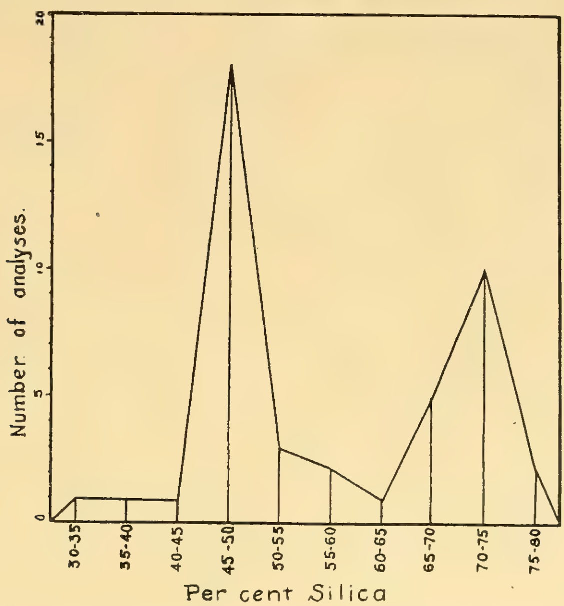

FIG. 9.—Silica content of specimens of the Duluth gabbro formation

Double differentiation.—A second feature of the rocks of the lopolith, which has a bearing on the process of differentiation, is the apparent break in the series. This is evident in plotting curves of variation in chemical or mineralogic constituents, and even more strikingly in a mathematical arrangement of the quantitative classification. Nothing in the outline of crystallization differentiation leads one to expect any sudden changes in rock types or any omissions in the series of intermediate rocks. A mass of rock with

[1] Frank F. Grout, "Two-Phase Convection in Igneous Magmas," *Jour. Geol.*, XXVI (1918), 481.

alkali feldspar is derived from gabbro only when a similar or larger amount of rock has separated with a medium to acid labradorite or andesine. No such rock is known at Duluth, though the small transition zones do exhibit zoned feldspars.

The arrangement of analyses according to the per cent of silica shows two well-defined and separated groups, one about 47 per cent silica and one about 72 per cent silica (see Fig. 9). The groups are evidently related to the two groups distinguished as gabbro and red rock. All the red rock contains more than 57 per cent silica;

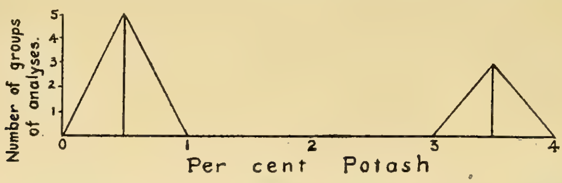

FIG. 10.—The potash content of the Duluth gabbro formation, as shown by available analyses (in groups).

no gabbro has as much as 57 per cent. The break appears even more sharply when the analyses are arranged in the order of silica per cent and a curve is drawn for the per cent of potash (see Fig. 10). All the groups of red rock analyses have more than three per cent of potash, while the gabbro groups all have less than 1 per cent. Although single analyses may show exceptional figures there is no real overlap.[1]

[1]

Silica per cent	Potash per cent, In detail	Potash per cent, By groups	
2.02	0		
32.90	0+	0.17	
35.81	0.33		
42.24	0.27		
45.65	1.05		
45.66	0.41		
46.45	0.34	0.56	
47.05	0.05		
47.10	0.92		
47.25	0.37		
47.79	0.53		
47.90	0.56	0.66	Gabbro
48.20	0.32		
49.15	1.61		
49.18	0.82		
49.39	0.10		
49.42	1.15	0.71	
49.78	0.46		
49.88	0.68		
50.43	0.34		
50.86	0.90		
52.48	1.75	0.95	
53.43	1.12		
56.60	0.45		

Silica per cent	Potash per cent, In detail	Potash per cent, By groups	
57.98	3.44		
61.09	3.65		
65.56	2.88	3.20	
66.36	3.05		
66.92	3.98		
68.36	4.48		
71.15	2.40		
71.81	1.92	3.66	Red rock
72.42	4.97		
73.28	4.50		
73.70	4.56		
73.91	2.78	3.18	
74.00	4.33		
75.78	1.06		

It is not suggested for a moment that the series at Duluth does not include all types in complete gradation, but the gradation zone is small, and the separation of two types is very complete. Even though some samples were selected to show intermediate rocks, the analyses show that they belong distinctly to one side or the other of a break in the series.

When these sharply divided groups are studied in detail, each is found to vary widely without crossing the limits of the group to

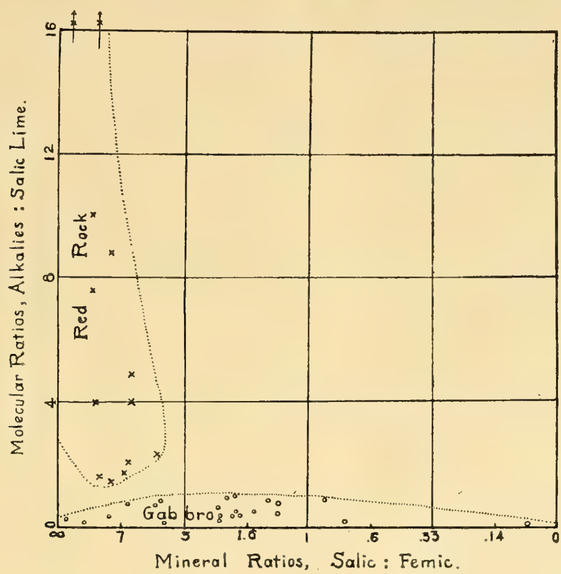

FIG. 11.—Diagram based on Duluth analyses, showing that the variation in the gabbro is in a different direction from the variation in the red rock. While the gabbro varies from salic to femic, it never becomes alkalic. While the red rock varies from alkalic to calcic, it nowhere becomes femic.

approach the other. There is no way to arrange all the gabbros in a single linear series, but this complexity in the gabbro group is entirely aside from the series grading toward red rock. It is a gradation of a really different character (see Fig. 11).

One series of rocks from peridotite to olivine gabbro and anorthosite, with some side branches to magnetitic gabbro and troctolite, varies chiefly in the quantities of minerals—labradorite, augite, olivine, and magnetite. In the main course of variation all four

gabbro minerals are present and the composition of minerals is surprisingly uniform throughout. When any mineral differs from the average the variation is not visibly related to the position or to the associated minerals.

A second type of variation is that from the general gabbro type to the granophyr. This is a change in mineral composition as well as a change in the essential minerals present (see Fig. 12). In the field this change comes with surprising abruptness, after the

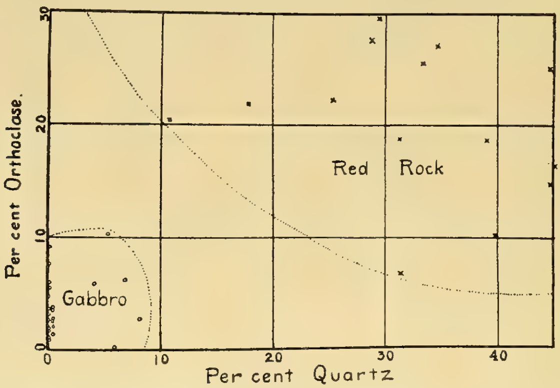

FIG. 12.—Diagram showing the break between gabbro and red rock at Duluth when plotted on the basis of quartz and orthoclase content.

monotony of slightly varying gabbro bands, with an extreme only occasionally. In a few feet after the reddish tinge of granophyr is seen in the interstices of the gabbro none of the gabbro minerals are visible in the rock.

This double process is distinctly contrary to the idea of Bowen's paper, and there are few suggestions of the sort in the literature. There are, indeed, suggestions of different types of differentiation. Bowen outlines two series from gabbro to alkaline types.[1] Harker has contrasted regional and local action.[2] Lane speaks of wet and dry differentiation.[3] However, there is evidence at Duluth of two

[1] N. L. Bowen, "Later Stages in the Evolution of Igneous Rocks," *Jour. Geol.*, XXIII (1915), December Supplement, p. 77.

[2] A. Harker, "Tertiary Igneous Rocks of Skye," *Mem. Geol. Survey of the United Kingdom* (1904), p. 419.

[3] A. C. Lane, "Wet and Dry Differentiation," *Tufts College Studies*, III, 39.

contrasting series in a single mass cooling in a single chamber, and a study of the literature of other districts makes it seem likely that this double sequence is a common thing.

The association of both granophyr and anorthosite as differentiates of normal gabbro is too common to have escaped observation. Each rock requires large bodies of magma for its production and each is of low specific gravity. Several geologists discuss these rocks as normal differentiates of gabbro, but no one has developed a satisfactory explanation of the manner in which the two rocks form. To be sure, a line of descent can be stated so that both are mentioned, but the suggested origin would lead one to expect them in very different field relations from those at Duluth. Thus, when peridotite, troctolite, and olivine gabbro had separated from the magma, the feldspar should begin to grow more acid and the olivine less abundant; but no such relation appears. Later, considerable magma of dioritic composition might yield crystals of gabbroic nature while itself as a liquid approaching the composition of a granite. However, before it reaches the composition of such a granophyr as the red rock of Duluth a large amount of feldspar must have crystallized from a magma too acid to yield basic labradorite; that is, at some stage, a quantity of diorite and granodiorite must have separated. No such rocks appear. Instead, there is a very narrow zone of granophyr diabase, in which the feldspars, to be sure, are zoned according to theory; but the zone is too small to yield the masses of red granophyr actually found.

Thus the characteristic rock series at Duluth is neither of Bowen's recognized series:[1] "gabbro, diorite, quartz diorite, granodiorite, granite"; nor "gabbro, diorite, syenite, granite." The series is rather (1) gabbro, (2) granophyr diabase, (3) granite, with the second member very small in bulk. This is believed to be a common sequence. Harker recently called attention to the general lack of intermediate rocks in such rock masses.[2]

[1] *Loc. cit.*

[2] A. Harker, "Differentiation in Intercrustal Magma Basins," *Jour. Geol.*, XXIV, 554.

TABLE I

CHEMICAL ANALYSES—GABBRO FROM DULUTH

	1	2	3	4	5	6	7	8	9*	10	11
Silica SiO_2	48.20	32.90	49.39	47.10	42.24	35.81	52.48	45.65	49.15	49.42	50.43
Alumina Al_2O_3	19.53	1.59	29.08	12.92	18.50	14.32	15.47	15.20	21.90	24.47	23.83
Ferric oxide Fe_2O_3	Trace	13.25	0.34	12.95	4.68	7.38	5.14	6.71	6.60	3.13	17.63
Ferrous oxide FeO	10.60	21.06	2.89	9.46	14.50	15.25	9.25	13.81	4.54	6.13	
Magnesia MgO	9.28	20.14	2.26	3.08	2.76	10.49	2.55	2.95	3.03	1.00	2.46
Lime CaO	8.51	0.50	13.06	10.29	10.36	7.23	7.27	6.33	8.22	8.45	4.79
Soda Na_2O	2.52	Trace	2.89	2.61	2.19	2.06	3.26	3.09	3.83	4.98	2.06
Potash K_2O	0.32	Trace	0.10	0.92	0.33	0.37	1.75	1.05	1.61	1.15	0.34
Combined water H_2O+	0.65	4.56	0.34	0.71	1.80	5.25	1.24	2.29	1.92	0.55	...
Moisture H_2O-	0.08	0.55	0.09	0.12	0.25	...	...	...	...	0.06	...
Carbon dioxide CO_2	0.02	0.10	Trace	...	1.67	Traces	...	...	...	...	...
Titania TiO_2	0.65	5.36	Trace	1.38	1.16	2.30	1.26	1.66	0.18	1.87	Trace
Phosphorus oxide P_2O_5	0.19	Trace	0.09	0.01	0.19	...	0.29	0.25	0.33	0.04	...
Sulphur S	0.03	0.65	None	...	...	...	...	...	...	0.11	...
Chromium oxide Cr_2O_3	Trace	0.04	Trace	...	...	...	...	...	...	...	...
Copper oxide Cu_2O	...	0.15	...	...	...	...	...	...	...	...	...
Manganous oxide MnO	0.14	0.40	0.04	0.80	0.13	0.18	0.51	0.71	...	0.11	...
Rarer elements	Trace	0.06	None	...	...	...	Traces	Traces	...	...	...
	100.72	100.71	100.57	101.63	100.76	100.62	100.47	99.70	100.80*	101.48	101.54
Specific gravity	2.963	3.353	2.770	...	...	3.07–3.10	2.81–2.84	2.84–2.86	...	...	2.79–2.802

* Original summation did not include P_2O_5 and TiO_2.

TABLE I—*Continued*

NORMS AND CLASSIFICATION

	1	2*	3	4*	5	6	7	8	9	10	11†
Quartz	...	...	...	...	...	...	5.6	...	...	...	...
Orthoclase	1.67	...	0.56	5.56	1.67	2.22	10.6	6.1	9.45	7.23	...
Albite	21.48	...	24.63	22.01	18.34	7.86	27.2	26.2	31.96	32.49	...
Anorthite	40.59	2.50	63.94	20.57	39.75	28.63	22.5	24.5	38.09	40.59	...
Nephelite	...	...	...	...	...	5.11	...	...	...	5.40	...
Corundum	...	...	0.71	...	...	...	...	...	...	...	...
Diopside	0.68	10.88	...	26.16	9.28	5.91	11.4	5.2	0.68	1.18	...
Hypersthene	12.54	4.85	6.34	9.26	4.27	...	11.6	19.5	4.16	...	...
Olivine	21.20	62.60	3.14	5.34	14.24	30.41	...	1.7	4.12	11.79	...
Magnetite	...	0.93	0.46	12.02	6.73	10.67	7.4	9.7	9.51	4.41	...
Ilmenite	1.22	8.43	...	2.74	2.28	4.41	2.4	3.2	0.30	3.50	...
Apatite	0.34	...	0.34	...	.34	...	.5	.5	.67	...	...

* Estimate based on the known secondary oxidation of part of the iron.

† "Not good for classification." H.S.W., PP 14, p. 431.

	1	2*	3	4*	5	6	7	8	9	10	11†
	Dosalic	Perfemic	Persalic	Salfemic	Salfemic	Salfemic	Dosalic	Salfemic	Dosalic	Dosalic	(Persalic)
	Perfelic	(Perfelic)	Perfelic	Perfelic	Perfelic	Perfelic	Perfelic	Perfelic	Perfelic	Perfelic	(Dofelic)
	Docalcic	(Docalcic)	Docalcic	Alkalicalcic	Docalcic	Docalcic	Alkalicalcic	Alkalicalcic	Docalcic	Alkalicalcic	(Docalcic)
	Persodic	....	Persodic	Dosodic	Persodic	Persodic	Dosodic	Dosodic	Dosodic	Dosodic	(Persodic)
	Hessose	....	Labradorose	Camptonose	Auvergnose	Auvergnose	Andose	Camptonose	Hessose	Andose	....
	II.5.4.5	V.5.4.–	I.5.4.5	III.5.3.4	III.5.4.5	III.5.4.5	II.5.3.4	III.5.3.4	II.5.4.4	II.5.3.4	

1. Olivine Gabbro. Sec. 23, T. 49 N., R. 15 W., West Duluth. F. F. Grout.
2. Peridotite. Sec. 34, T. 49 N., R. 15 W., Short Line Park. F. F. Grout.
3. Anorthosite Sec. 19, T. 50 N., R. 14 W., North of Proctor. F. F. Grout
4. Olivine Gabbro. Sec. 33, T. 49 N., R. 15 W., Short Line Park. G. S. Nishihara.
5. Gabbro Pegmatite. Sec. 33, T. 49 N., R. 15 W., Short Line Park. G. S. Nishihara
6. Troctolite. Sec. 22, T. 50 N., R. 15 W., North of Proctor. A. N. Winchell. *Am. Geol.*, XXVI, 284.
7. Orthoclase Gabbro. Down town at Duluth. A. N. Winchell. *Am. Geol.*, XXVI, 293.
8. Hornblende Orthoclase Gabbro. Down town at Duluth. A. N. Winchell. *Am. Geol.*, XXVI, 293.
9. Hornblende Gabbro. At Duluth. A. Streng. *Neues Jahrbuch für Mineralogie, Geologie und Paleontologie*, 1877, p. 113.
10. Gabbro, probably of the feldspathic type. Near the center of Sec. 33, T. 50 N., R. 14 W., Duluth. G. H. Stone. *Jour. Geol.*, XVIII, 656.
11. Gabbro, feldspathic type. Sec. 34, T. 50 N., R. 14 W., Duluth. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, Final Rep.*, V, 85.

TABLE I—*Continued*

ANALYSES OF DULUTH GABBRO, NORTHEAST OF THE TYPE LOCALITY

	12	13	14	15	16	17	18
Silica SiO_2	2.02	45.66	46.45	47.70	47.90	53.43	56.60
Alumina Al_2O_3	2.68	16.44	21.30	19.04	19.92	13.81	17.84
Ferric oxide Fe_2O_3	80.78 (Ferric and ferrous oxide together)	0.66	0.81	0.87	4.92	5.08	2.55
Ferrous oxide FeO		13.90	9.57	8.84	9.78	9.86	4.09
Magnesia MgO	...	11.57	7.90	8.65	4.55	4.64	3.16
Lime CaO	Trace	7.23	9.83	8.96	8.56	8.25	6.28
Soda Na_2	...	2.13	2.14	2.53	2.75	2.51	4.45
Potash K_2O	...	0.41	0.34	0.53	0.56	1.12	0.45
Combined water H_2O+	...	0.83	1.02	1.38	0.76	0.27	3.20
Moisture H_2O-	...	0.07	0.14	...	...	...	...
Carbon dioxide CO_2	...	...	...	Trace	n.d.	...	n.d.
Titania TiO_2	12.09	0.92	1.19	1.80	0.57	...	1.59
Phosphorus oxide P_2O_5	0.03	0.05	0.02	n.d.	n.d.	...	0.14
Chromium oxide Cr_2O_3	2.40	Trace	...	...	...	...	...
Manganous oxide MnO	...	Trace	Trace	Trace	...	Trace	...
Nickel oxide NiO	...	0.16	0.04	...	...	...	...
Other elements	...	...	...	Traces	Traces	...	Traces
	99.90	100.03	100.75	100.30	100.27	98.97	100.35
Specific gravity	...	...	...	2.89	2.93	...	2.38*

* Evidently an error but correctly quoted.

TABLE I—*Continued*

NORMS AND CLASSIFICATION

	12	13	14	15	16	17	18
Quartz	....	....	....	....	....	7.68	8.9
Orthoclase	....	2.2	1.7	2.8	3.3	6.67	2.8
Albite	....	17.8	17.8	21.0	23.1	20.96	37.7
Anorthite	....	34.2	47.8	39.2	40.0	23.07	27.2
Diopside	....	1.4	0.8	4.5	2.0	14.78	3.4
Hypersthene	....	10.1	11.1	12.7	19.8	18.10	11.5
Olivine	....	30.3	16.8	13.9	1.8	....	....
Magnetite }	95.27	0.9	1.2	1.4	7.2	7.42	3.7
Ilmenite }		2.6	2.3	3.4	1.1	....	3.1
Apatite	....	....	....	....	....	....	....
	Perfemic	Salfemic	Dosalic	Dosalic	Dosalic	Salfemic	Dosalic
	(Perfelic)	Perfelic	Perfelic	Perfelic	Perfelic	Dofelic	Perfelic
	....	Docalcic	Docalcic	Docalcic	Docalcic	Docalcic	Alkalicalcic
	....	Persodic	Persodic	Persodic	Persodic	Dosodic	Persodic
	X	Auvergnose	Hessose	Hessose	Hessose	X	Beerbachose
	V.5—	III.5.4.5	II.5.4.5	II.5.4.5	II.5.4.5	III.4.4.4	II.5.3.5

12. Gabbro magnetite. On the south side of Iron Lake, Sec. 36, T. 65 N., R. 3 W. R. S. Robertson. *Minn. Geol. and Nat. Hist. Survey Bull. 6*, p. 141.
13. Gabbro. Sec. 19, T. 63 N., R. 9 W. H. N. Stokes. *Jour. Geol.*, I, 712.
14. Gabbro, representative. Sec. 35, T. 61 N., R. 12 W. H. N. Stokes. *Jour. Geol.*, I, 712.
15. Olivine Gabbro. Birch Lake. H. N. Stokes. *Am. Geol.*, XXVI, p. 181.
16. Diabase Gabbro. East side of Birch Lake. A. N. Winchell. *Am. Geol.*, XXVI, 374.
17. Gabbro with quartz. Endomorphic contact rock. Sec. 11, T. 63 N., R. 5 W. Dodge and Sidener. *Minn. Geol. and Nat. Hist. Survey, Final Rep.* V, 543.
18. Quartz Gabbro. Sec. 12, T. 64 N., R. 6 W. Little Saganaga Lake. A. N. Winchell. *Am. Geol.*, XXVI, p. 352.

TABLE I—*Continued*

ANALYSES OF SILLS AND MASSES SUPPOSED TO BE RELATED TO THE DULUTH GABBRO

	19	20	21	22	23	24
Silica SiO_2	49.18	49.88	50.86	47.25	49.78	47.05
Alumina Al_2O_3	19.01	18.55	15.72	31.56	29.37	32.03
Ferric oxide Fe_2O_3	0.89	2.06	9.77	....	0.34 }	2.01
Ferrous oxide FeO	7.79	8.37	2.48	2.29	0.60 }	
Magnesia MgO	6.42	5.77	3.55	0.27	1.07	0.15
Lime CaO	9.12	9.70	10.52	15.39	11.86	15.85
Soda Na_2O	3.32	2.59	3.89	2.52	4.39	1.00
Potash K_2O	0.82	0.68	0.90	0.37	0.46	0.05
Combined water H_2O+	2.06	1.04	2.53	0.40	1.76	1.36
Moisture H_2O-	....	....	....	....	....	....
Carbon dioxide CO_2	Trace	....	....	....	....	....
Titania TiO_2	1.09	1.19	....	....	None	....
Phosphorus oxide P_2O_5	....	0.16	....	....	Traces	....
Manganous oxide MnO	0.51	0.09	....	....	0.08	....
Barium oxide BaO	None	0.02	....	....	None	....
Other elements	Traces	....	....	....	Traces	....
	100.21	100.21	100.22	100.05	99.80	99.50
Specific gravity	2.84	2.923–2.970	....	About 2.7	2.676	....

TABLE I—*Continued*

ANALYSES OF RED-ROCK INTRUSIVES AT DULUTH

	25	26	27	28
Silica SiO_2	66.92	66.36	75.78	65.56
Alumina Al_2O_3	12.51	13.33	11.09	10.06
Ferric oxide Fe_2O_3	4.36	7.89	2.09	14.40
Ferrous oxide FeO	3.93	2.96	....	0.23
Magnesia MgO	1.66	1.20	0.65	0.73
Lime CaO	1.20	2.14	0.86	0.96
Soda Na_2O	3.45	2.63	6.43	2.25
Potash K_2O	3.98	3.05	1.06	2.88
Combined water H_2O+	1.25	1.21	1.82	0.86
Moisture H_2O-	0.20	....	....	....
Carbon dioxide CO_2	0.02	....	....	....
Titania TiO_2	0.69	....	....	....
Zirconia ZrO_2	0.22	....	....	....
Phosphorus oxide P_2O_5	0.11	....	....	....
Sulphur S	0.04	....	....	....
Manganous oxide MnO	0.16	....	....	....
Barium oxide BaO	0.06	....	....	....
	100.76	100.77	99.78	97.93
Specific gravity	2.721	....	....	....

TABLE I—*Continued*

NORMS AND CLASSIFICATION

	19	20	21	22	23	24
Quartz	....	....	3.2	....	....	6.60
Orthoclase	5.00	3.9	5.6	2.22	2.8	....
Albite	27.77	22.0	33.0	15.20	28.8	8.38
Anorthite	34.47	37.0	22.5	73.40	58.7	78.68
Nephelite	....	....	....	3.41	4.5	....
Corundum	....	....	....	....	....	1.53
Diopside	8.90	8.9	19.3	2.67	....	....
Hypersthene	2.76	21.8	....	....	....	1.46
Olivine	15.74	....	....	2.70	2.5	....
Magnetite	1.39	3.0	8.1	....	0.5	1.39
Ilmenite	2.13	2.3	....	....	....	....
Hematite	....	....	4.2	....	....	....
Wollastonite	....	....	2.0	....	....	....
	Dosalic Perfelic Docalcic Dosodic	Dosalic Perfelic Docalcic Dosodic	Dosalic Perfelic Alkalicalcic Dosodic	Persalic Perfelic Docalcic Persodic	Persalic Perfelic Docalcic Persodic	Persalic Perfelic Percalcic Persodic
	Hessose	Hessose	Andose	Labrado-rose	Labrado-rose	Persodic Canadase
	II.5.4.4	II.5.4.4	II.5.3.4	I.5.4.5	I.5.4.5	I.5.5.5

19. Olivine diabase. Pigeon Point. A. N. Winchell. *Am. Geol.*, XXVI, 213.
20. Olivine gabbro. Pigeon Point. W. F. Hillebrand. *U.S. Geol. Survey Bul. 109*, p. 63.
21. "Altered Gabbro. East of Baptism River." Dodge and Sidener. This probably is "Beaver Bay diabase." *Minn. Geol. and Nat. Hist. Survey Bul. 2*, p. 79.
22. Anorthosite. At mouth of Split Rock River, quoted from R. D. Irving. *U.S. Geol. Survey Mon.*, V, p. 438.
23. Anorthosite. Carlton Peak. A. N. Winchell. *Am. Geol.*, XXVI, 281.
24. Anorthosite. At the foot of Caribou Peak. C. F. Sidener.

TABLE I—*Continued*

NORMS AND CLASSIFICATION

	25	26	27	28
Quartz	25.50	33.00	33.00	38.28
Orthoclase	23.91	17.79	6.67	17.24
Albite	28.82	22.53	50.83	18.86
Anorthite	5.28	10.56	....	4.73
Corundum	0.61	1.73	....	1.53
Zircon	0.37	....	....	....
Diopside	....	....	3.24	....
Hypersthene	6.87	3.00	0.10	1.80
Acmite	....	....	3.23	....
Magnetite	6.26	9.51	....	0.93
Ilmenite	1.37	....	....	....
Hematite	....	1.28	0.96	13.76
Apatite	0.34	....	....	....
	Dosalic Dofelic Domalkalic Sodipotassic	Dosalic Quarfelic Domalkalic Sodipotassic	Persalic Dofelic Peralkalic Persodic	Dosalic Quarfelic Domalkalic Sodipotassic
	Adamellose	X	Noyangose	X
	II.4.2.3	II.3.2.3	I.4.1.5	II.3.2.3

25. Red Rock. N.W. corner Sec. 27, T. 50 N., R. 14 W. F. F. Grout.
26. Red Granite. Rice's Point, Duluth. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 13th Ann. Rep.*, p. 100.
27. Red Granite. Rice's Point, Duluth. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 10th Ann. Rep.*, p. 204.
28. Red Granite. East of Lester River, East Duluth. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 13th Ann. Rep.*, p. 100.

TABLE I—*Continued*

ANALYSES OF RED-ROCK INTRUSIVES NORTHEAST OF DULUTH SUPPOSED TO BE RELATED TO THE DULUTH GABBRO

	29	30	31	32	33	34	35	36	37	38
Silica SiO_2	57.98	61.09	68.36	72.42	74.00	73.91	73.70	71.15	71.81	73.28
Alumina Al_2O_3	13.58	15.34	13.76	13.04	12.04	14.89	12.87	12.40	12.82	11.83
Ferric oxide Fe_2O_3	3.11	5.74	2.65	0.68	0.78	2.27	3.76	5.21	6.02	4.61
Ferrous oxide FeO	8.68	3.69	2.75	2.49	2.61	1.70	0.31	0.75		0.56
Magnesia MgO	2.87	1.33	0.68	0.58	0.42	Trace	0.11	1.13	0.56	0.36
Lime CaO	2.01	3.10	0.70	0.66	0.85	0.27	0.14	1.90	2.26	1.04
Soda Na_2O	3.56	3.41	3.56	3.44	3.47	2.64	3.63	1.70	2.51	1.66
Potash K_2O	3.44	3.65	4.48	4.97	4.33	2.78	4.56	2.40	1.92	4.50
Combined water H_2O+	2.47	1.80	0.98	1.21	0.86	1.01	0.57	2.12		1.82
Moisture H_2O-										
Titania TiO_2	1.75		1.57	0.40	0.34		0.12			
Phosphorus oxide P_2O_5	0.29		0.33	0.20	0.06		Trace			
Sulphuric oxide SO_3			0.66							
Manganous oxide MnO	0.13			0.09	0.05		0.07			
Barium oxide BaO	0.04			0.15	0.12					
Other elements	Traces			Traces	Traces					
	99.91	99.15	100.48	100.37	99.93	99.47	99.84	98.76	97.90	99.66
Specific gravity				2.620	2.565					

TABLE I—*Continued*

NORMS AND CLASSIFICATION

	29	30	31	32	33	34	35	36	37	38
Quartz	11.1	17.7	28.0	29.4	33.2	46.44	34.7	45.12	40.08*	43.44
Orthoclase	20.0	21.2	26.7	30.0	25.6	16.68	27.2	14.46	11.12	26.69
Albite	29.9	28.8	29.9	28.8	29.3	22.53	30.4	14.15	20.96	14.15
Anorthite	10.0	15.3	3.3	3.2	4.2	1.39	0.6	9.45	11.12	5.28
Corundum	0.5	....	1.8	0.8	....	6.94	1.7	3.57	2.55	2.24
Hypersthene	17.7	5.4	1.9	5.0	4.6	1.32	0.3	2.80	11.30	0.90
Magnetite	8.0	8.1	3.9	0.9	1.2	3.25	0.9	2.55	....	1.87
Ilmenite	3.4	....	3.1	0.8	0.6	....	....	....	....	....
Hematite	....	....	....	....	....	....	3.2	3.52	....	3.36

* Assuming that some ferric iron is secondarily oxidized, as is evident.

29	30	31	32	33	34	35	36	37	38
Dosalic Dofelic Domalkalic Sodipotassic	Dosalic Dofelic Domalkalic Sodipotassic	Persalic Dofelic Peralkalic Sodipotassic	Persalic Dofelic Peralkalic Sodipotassic	Persalic Dofelic Domalkalic Sodipotassic	Persalic Quarfelic Peralkalic Sodipotassic	Persalic Dofelic Peralkalic Sodipotassic	Persalic Quarfelic Alkalicalcic Sodipotassic	Persalic Quarfelic Alkalicalcic Dosodic	Persalic Quarfelic Domalkalic Dopotassic
Adamellose	Adamellose	Liparose	Liparose	Toscanose	Alaskose	Liparose	Riesenose	Dosodic Riesenase	Mihalose
II.4.2.3	II.4.2.3	I.4.1.3	I.4.1.3	I.4.2.3	I.3.1.3	I.4.1.3	I.3.3.3	I.3.3.4	I.3.2.2

29. "Intermediate rock," selected to show the type of rock between gabbro and red rock. Pigeon Point. W. F. Hillebrand. *U.S. Geol. Survey Bull. 109* p. 63.
30. Red Granite. Pigeon Point. M. E. Wadsworth. *Minn. Geol. and Nat. Hist. Survey, Final Rep.*, V, p. 303.
31. Red Rock. Pigeon Point. J. E. Whitfield. *U.S. Geol. Survey Bull. 109*, p. 90.
32. Red Rock. Pigeon Point. W. F. Hillebrand. *U.S. Geol. Survey Bull. 109*, p. 56.
33. Red Rock, porphyritic. Pigeon Point. W. F. Hillebrand. *U.S. Geol. Survey Bull. 109*, p. 56.
34. Red Rock. Island south of Pigeon Point. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 13th Ann. Rep.*, p. 100.
35. Red Rock, porphyritic. Little Brick Island off Pigeon Point. L. G. Eakins. *U.S. Geol. Survey Bull. 109*, p. 58.
36. Granite, pink. West side of Beaver Bay. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 13th Ann. Rep.*, p. 100.
37. Granite, purplish gray. West side of Beaver Bay. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, Final Rep.*, V, 400.
38. Red Granite. Third island east of Beaver Bay. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 13th Ann. Rep.*, p. 100.

TABLE II

CLASSIFICATION OF IGNEOUS ROCK SERIES FROM SEVERAL DISTRICTS

DULUTH	SKYE	SUDBURY	PURCELL	CARROCK FELL	PRESTON	JULIANA-HAAB	SWEDEN	PALISADES	GOWGANDA	ST. DAVIDS HEAD	ADIRON-DACKS	CORTLANDT
Gabbro Series	Diabase and Dolerite	Diabase and Norite	Diabase Sills	Gabbro	Gabbros		Olivine-Diabase, Peridotite, Anorthosite and Iron Ores	Diabase	Sills of Gabbro and Granophyr-Diabase	Various Gabbros	Gabbros, Anorthosite and Iron Ore	Diorite, Gabbro, Norite, Pyroxenite
I.5.4.5											I.5.4.5	
I.5.4.5												
I.5.4.5												
I.5.5.5												
									II.5.2.5			
							II.5.3.3					II.5.3.3
II.5.3.4							II.5.3.4					II.5.3.4
II.5.3.4												II.5.3.4
II.5.3.4												II.5.3.4
II.5.3.5									II.5.3.5	II.5.3.5		
		II.5.4.3									II.5.4.3	II.5.4.3
											II.5.4.3	II.5.4.3
II.5.4.4	II.5.4.–	II.5.4.4					II.5.4.4					
II.5.4.4		II.5.4.4										
II.5.4.4												
II.5.4.5	II.5.4.5			II.5.4.5								
II.5.4.5	II.5.4.5											
II.5.4.5	II.5.4.5											
II.5.4.5												
	II.5.5.5					II.6.1.4						
III.5.3.4			III.{4/5}.5.4			II.7.1.4			III.5.2.4			
III.5.3.4								III.5.3.4		III.5.3.4	III.5.3.4	
								III.5.3.4			III.5.3.4	
								III.5.3.4				
					III.5.3.5			III.5.4.4		III.5.4.4		
			III.5.4.4				III.5.4.4	III.5.4.4				
III.5.4.5			III.5.4.5		III.5.4.5			III.5.4.4				
III.5.4.5					III.5.4.5			III.5.4.4				
III.5.4.5								III.5.4.5				
		III.5.5.5						III.5.4.5				
						III.6.1.3						III.6.3.4
	IV.5.4.4						IV.5.4.4	IV.5.4.4			IV.5.4.3	IV.5.3.3
							IV.5.4.4	IV.5.4.4				IV.5.3.4
											IV.5.–.–	IV.5.3.4
											IV.6.4.4	
V.5.4.–	V.5.4.4											
V.5.–.–												

			Intermediate Rock				Monzonite					
....	....	....	II.4.4.3	....	....	....	II.4.3.4	....	....	....	....	....
Red Rock	Granophyr	Syenite and Granite	Granite		Oligoclase Granite		Granite	Granophyr-Diabase	Aplite	Aplite	Granite and Syenite	Granite
I.3.1.3											I.3.1.3	
									I.3.1.5			
I.3.2.2												
			I.3.2.3									
					I.3.2.4							
I.3.3.3												
I.3.3.4												
		I.4.1.2										
I.4.1.3							I.4.1.3					
I.4.1.3												
I.4.1.3												
				I.4.1.4						I.4.1.4		
I.4.1.5												
I.4.2.3	I.4.2.3	{I, II} 4.2.3									I.4.2.3	
	I.4.2.3										I.4.2.3	
											I.4.2.3	
											I.4.2.3	I.4.2.4
											I.5.2.3	
											I.5.2.4	
II.3.2.3		II.3.2.3	II.3.2.3									
II.3.2.3												
		II.3.4.3										
		II.4.1.4				II.4.1.4						
II.4.2.3												
II.4.2.3												
II.4.2.3												
		II.4.2.4						II.4.2.4				
		II.4.2.4						II.4.3.4			II.4.3.3	
		II.4.2.4									II.5.2.3	
		II.4.2.4									II.5.3.4	

COMPARISON WITH OTHER DISTRICTS

Data from several other districts are given in Table II. The method of comparison is modeled after the mathematical statement of the quantitative classification.[1] However, instead of using different bases for distinguishing rocks of the different classes, the plan in Table II is to use the same criteria for all rocks, making the figures strictly comparable through the whole table. The first term is the class (I to V) in the quantitative system. The second expresses, by groups (1 to 9), the ratios of quartz to feldspar, or lenads to feldspar. The third and fourth terms similarly express the ratio of alkalies to the lime of salic minerals, and the ratio of potash to soda, in molecular terms. These are the figures given below the norms in Table I of analyses of the Duluth lopolith.

Scarcity of intermediate rocks.—The impression obtained from the Duluth series is carried out in the others. There are few intermediate rocks in any of the districts. The samples contrast almost as sharply as at Duluth, though none seem to have as complete a series of analyses. The main rocks of the associated sequences are members of the gabbro family and granites. One rock collected by Daly in the Purcell sills is really intermediate, and this is a rock which was carefully selected with the idea of showing its transitional nature. Probably the Swedish monzonite and some syenites of the Adirondacks are also intermediate, but the papers describing them are not very definite as to their occurrence and relation. Even if the proof of gradational types is clear, as it is at Duluth, the data may well be taken as evidence that intermediate rock is less abundant than the several types on either side of the break. The sharpness of separation of types in the field has often been noted in regions of differentiated rocks.[2] To be sure it may be argued that a collector would choose clear types rather than a mixed indefinite specimen, but the facts at Duluth argue against any such condition. Here a good series showing variations of gabbro is available; but no series connects the several gabbros with the red rock; and, as

[1] Whitman Cross, J. P. Iddings, L. V. Pirsson, and H. S. Washington, *Quantitative Classification of Igneous Rocks*. University of Chicago Press, 1903.

[2] L. V. Pirsson and W. N. Rice, "The Geology of the Tripyramid Mountain," *Am. Jour. Sci.*, XXXI, 291.

said before, some were selected with the expressed intention of showing what the intermediate rocks are like.

In several large igneous bodies one of the differentiates has assumed intrusive relations to the others. In such cases it might be assumed that the disturbance is responsible for the abrupt change from one extreme to another; possibly the large amount of intermediate rock required by theory has been eroded, or is concealed in depth. Such arguments may apply to batholiths, but not to an intrusion with a floor, especially if it is as well exposed as at Duluth. Granted that there is a lack of intermediate rock at Duluth, the corresponding lack elsewhere indicates that intermediate rocks were never formed in any large quantity.

An argument for immiscible separation.—If this apparent break in the series is as normal and characteristic as it appears from the table, it gives a rather different impression from the simple sequence that has been suggested for the results of differentiation. Some modification or restatement of the outline of crystallization differentiation may bring it into closer accord with known series, but the clear impression from the series here tabulated is that two processes have been at work either successively or simultaneously.

If crystallization differentiation produced the banded gabbro, with differentiates ranging from peridotite and iron ore to anorthosite, what other processes can be conceived which might yield the red-rock differentiate? It cannot be that one is a regional and the other a local variation, for it is all in the same chamber. It is very likely to be a contrast between wet and dry. The first type of differentiation occurs in the presence of a very small amount of water (though biotite occurs even in the gabbro); and if the crystallization results in a concentration of water in the mother liquor, a point may be reached where the water has an effect not known in the earlier stages. Even in this case it is not clear why the water concentrating gradually would not yield a series of intermediate rocks in considerable volume.

The abruptness of the gradation leads almost conclusively to the idea of a separation of an immiscible liquid. This would be favored by the increased amount of water. Water was certainly abundant, as is indicated by numerous miarolitic cavities in the

red rock. It seems doubtful if any other process than the separation of immiscible fractions could operate with the separation of crystals to give such a distinct differentiate.

SUMMARY

The rocks of the Duluth gabbro lopolith are found to fall naturally into two series, one related to the gabbro family, the other more closely to the granites. Intermediate types are rare, though in the field the gradation between types is visibly complete. The abruptness of the separation in the field as well as in the arrangements on the basis of laboratory data indicates that the process involved in the separation of granite and gabbro was of a different nature from the more easily understood process by which a variety of phases developed in the gabbro. The several modifications of the gabbro probably resulted from a differentiation by crystallization during convection, aided by a slight amount of settling of crystals. Before the solidification was complete the granitic magma must have separated from the gabbro, probably by some other process, for the process giving variety to the gabbro seemed to produce no modification in it approaching the granite. The evidence is strong that differentiation of two sorts may occur in a single magma chamber. If crystallization and settling and convection are involved in the main process, it is interesting to suggest other possibilities for the other process. The difference may be due largely to a difference in the concentration of water, but the field and laboratory studies both strongly suggest an immiscible separation of the red rock from the gabbro.

November, 1918

POST-GLACIAL MOLLUSCA FROM THE MARLS OF CENTRAL ILLINOIS[1]

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The study of the biota contained in marl beds, and in other deposits lying upon the till of the late Wisconsin ice sheet, has added greatly to our knowledge of the post-glacial distribution of many mollusks and other animals, and has often provided data bearing on the changes of climate which have occurred during the interval between the retreat of the Wisconsin ice and the present time. The material that forms the basis for the present contribution adds to our knowledge concerning the post-glacial distribution of a few lacustrine and fluviatile forms of mollusks.

My thanks are due Dr. T. E. Savage, of the University of Illinois, for the opportunity of examining the material as well as for stratigraphic data bearing upon the deposit containing the collections; Dr. V. Sterki and Dr. Bryant Walker for the examination of critical material; and Professor Frank Smith for assistance in collecting material from the vicinity of Mahomet.

Marl deposits are extensively distributed in Michigan, Wisconsin, Maine, New Jersey, and other localities, being better known in the states named than elsewhere. Indiana, Ohio, and Illinois also contain marl beds of greater or less size, but these have not been as exhaustively studied for their biota. Marl deposits have rarely been reported from Illinois, a condition due to lack of observation rather than to absence from the territory.

The study of these marl deposits is of great interest and some value, a comparison of the marl fauna with the recent fauna usually showing a change from cold to temperate climate. Many species also indicate a more southward distribution during early post-glacial time. It is of importance that the marl deposits of the state

[1] *Contribution from the Museum of Natural History*, University of Illinois, No. 1.

of Illinois, of which there are doubtless many, should be examined carefully and their biota compared with the recent biota of the same region and with localities within the range of the different species. This is especially true as regards deposits of an interglacial character.

Three new marl deposits are discussed in the present paper, two near Mahomet, on the Sangamon River, and the third on the campus of the University of Illinois, in Urbana.

THE URBANA DEPOSITS

Excavations for the new greenhouse and for drains in the neighborhood show the following superposition of strata (section made by Dr. T. E. Savage):

Section of ditch through old pond

4.	Top soil or black clay without pebbles, grading down into number 3 below	20–24 inches
3.	Clay, dark above, becoming light gray and more calcareous below; containing numerous mollusks	18–20 inches
2.	Marl or limestone composed of more or less completely broken shells somewhat consolidated by cement of $CaCo_3$	8–12 inches
1.	Glacial till, pebbly, gray	6–12 inches

The depth of the section was about four feet.

The locality from which these fossils came is in a depression northeast of the new greenhouses, near the forest nursery. The topography at this place suggests a pond of considerable size and the molluscan life indicates quite a depth of water, at least in the center of the lake or pond. The glacial till here is the Champaign till sheet, and the body of water evidently stood in a kettle hole on the northern side of the Champaign moraine, which extends northwest and southeast through Champaign and Urbana (Leverett, 1899, pl. vi). This till sheet is of early Wisconsin age, and the relation of the marl to the till suggests that the pond or lake may have been inhabited by the mollusks when the late Wisconsin ice was resting at the Valparaiso moraine. The cemented character of the marl numbered 2 in the section also suggests considerable age. This lake or pond may have drained northeastward through the present Salt Fork Valley.

The fauna from these marls also indicates a cooler climate when the pond was occupied by the living mollusks, the southern limit of distribution of several of the species now being at a considerable distance north of this locality. Other extinct forms in this deposit were previously known only from the marls of Maine and Michigan. The distribution and other relations of the species from the Urbana deposits are shown in Table I; *x* indicates that no authentic Illinois records are known.

TABLE I

MOLLUSCAN DISTRIBUTION

Molluscan Species	Now Living in Urbana or Vicinity	Nearest Illinois Locality	Distance from Urbana in Miles	Fossil Only	Known from Marl of Michigan
Sphaerium rhomboideum	....	Menard Co.	80	....	....
Sphaerium occidentale	....	Fulton Co.	95	....	*
Musculium rosaceum	....	*x*	....	....	....
Musculium truncatum	#	....	....	....	*
Pisidium adamsi affine	....	Winnebago Co.	140	....	*
Pisidium contortum	....	*x*	....	....	*
Pisidium costatum	....	*x*	....	*	*
Pisidium tenuissimum calcareum	....	*x*	....	*	*
Pisidium variabile	....	Mason Co.	95	....	*
Pisidium vesiculare	....	*x*	....	....	*
Valvata sincera	....	*x*	....	....	*
Valvata tricarinata	....	Mason Co.	95	....	*
Physa gyrina	#	....	....	....	*
Physa sayii	....	Peoria Co.	81	....	....
Planorbis trivolvis	#	....	....	....	*
Planorbis parvus urbanensis	....	....	....	*	....
Planorbis altissimus	....	....	....	*	....
Galba caperata	#	....	....	....	*
Galba obrussa decampi	....	Lake Co.	140	....	*
Galba reflexa	....	McLean Co.	48	....	*

An analysis of this table brings out several interesting features, as noted below:

Species now living in same territory	4
Species now living in same latitude	10
Species not now living in state (not yet reported)	8
Extinct species	4
Percentage of species also known from marl beds of Michigan	75 per cent
Percentage of marl fauna now living in Illinois	70 per cent
Percentage of marl fauna now living in vicinity of Urbana	20 per cent

It would be of great interest to compare other marl faunas of Illinois with the one herein described. It is quite probable that the new species, as well as the species now showing a more southward distribution in Pleistocene time, will also occur in other marl deposits of the state.

The collections are in the Museum of Natural History of the University of Illinois, and are included in numbers Z10755 to Z10803, inclusive.

ANNOTATED LIST OF SPECIES

SPHAERIIDAE

Sphaerium rhomboideum Prime

A portion of one right valve was the only evidence of the presence of this finger-nail clam, which is common, living in the northern part of the state.

Sphaerium occidentale Prime

One valve, apparently of this species, was observed by Dr. Sterki with a lot of Pisidia. It is a common species of the swales and small ponds in the northern half of the state.

Musculium truncatum (Linsley)

Rather plentiful. A number of specimens differ from the typical form in being larger, with narrower, more elevated beaks, which are inclined forward. *Truncatum* is a common species in the northern part of Illinois. The beaks of all these Musculia are strongly calyculate.

Musculium cf *rosaceum* (Prime)

A single valve is referred doubtfully to this species by Dr. Sterki. A single record of this species from the state is given by Wolf (1870, p. 27) for Fulton County, but the identification is doubtful. There is no authentic record from Illinois as far as known to me.

Pisidium tenuissimum calcareum Sterki

This fossil *Pisidium* is the most abundant mollusk in the marl bed under discussion, showing considerable variation. It has been previously known from the marls of Maine and Michigan, and its presence so far south of its hitherto recorded distribution is of great interest and indicates clearly a colder climate in early post-glacial time.

Pisidium costatum Sterki

Next to *Pisidium tenuissimum calcareum* this species is the most abundant mollusk in the collection. Of this species Dr. Sterki says, "For years I thought it might be a form of *Pisidium medianum*, but rather different; this find appears rather to vindicate it." It has not been observed among recent Pisidia and was previously known only from marl deposits in Michigan and Maine. With the previous species this southward distribution indicates a climatic change.

Pisidium vesiculare Sterki

A few rather small but characteristic specimens occur in the collection. This species is not known from Illinois as a living mollusk. It has been observed in the marls of Michigan.

Pisidium variabile Prime

One valve of this abundant species was found in the collection. It is a common species in the northern part of Illinois, both fossil and living, and it is strange that only a trace of its presence has been left in the bed at Urbana.

Pisidium adamsi affine Sterki

A single valve of a juvenile individual occurred with other Pisidia. It is known only from Winnebago County (collected by A. A. Hinkley).

Valvatidae

Valvata tricarinata (Say)

Not common. The individuals are sharply tricarinate, though the majority are immature. This species is a common mollusk in the ponds, lakes, and streams of the northern part of the state.

Valvata sincera (Say)

This valvata is quite common in the deposit. These are the first authentic specimens of *sincera* from an Illinois locality, specimens hitherto identified as *sincera* proving, upon examination, to be *lewisii* (see Baker, 1806, p. 91). The Urbana specimens of *sincera* were referred to Dr. Bryant Walker, who declared them to be quite typical of the species. This record indicates a wider southward distribution in early post-glacial time.

Physidae

Physa sayii Tappan ?

A single immature shell is referred doubtfully to this species. It has the characteristic shape of a half-grown *sayii* and is covered with heavy impressed spiral lines. The individual has 4½ whorls and is 12 mm. long. *Sayii* is a common species in northern Illinois and the states to the north.

Physa gyrina Say

The shells of this protean species occur in abundance in the marl deposit; the greater number of individuals, however, are immature, only about 3 per cent being fully mature. The largest specimen has 6 whorls and measures 26 mm. in length. *Gyrina* is distributed quite generally over the state and in the states north of Illinois.

Planorbidae

Planorbis trivolvis Say

Not common in the marl deposit and the majority of individuals are immature. *Trivolvis* is a very common species in Illinois and adjacent states.

Planorbis parvus urbanensis Baker, n. var.[1]

This new form of *Planorbis parvus* occurred sparingly in the marl deposits and was apparently not as abundant in the post-glacial pond as the typical *parvus* usually is in ponds of a similar character. Typical *parvus* occurs living in the vicinity of Urbana.

Planorbis altissimus Baker, n. sp.[1]

This new species of *Planorbis* is represented by a few adult individuals and a number of young and immature specimens. It was apparently not as common as the variety of *parvus* listed above.

Lymnaeidae

Galba reflexa (Say)

This Lymnaeid occurs plentifully in the marl deposit and is very abundant and variable; the majority of individuals, however, are young or immature. *Reflexa* is commonly distributed over the greater part of Illinois.

[1] The new *Planorbes* will be described in the current number of the *Nautilus*.

Galba caperata (Say)

Caperata is abundantly distributed over the northern half of Illinois. The marl specimens are numerous, quite typical, and mostly mature.

Galba obrussa decampi (Streng)

This characteristic marl fossil is common in the Urbana marl deposit. The specimens show some peculiarities of interest. The whorls are very heavily shouldered, the sutures almost channeled, and the aperture is separated from the body whorl by a deep channel, causing the inner and outer lips to become continuous and the aperture to become auriform. There is some variation in the height of the spire and in the relative width of the shell. The collection contains both adult and young shells.

The Urbana shells give the most southern record for the distribution of the species; the only recent records from the state are in Lake and McHenry counties, and the only fossil record from post-glacial deposits is near Chicago. It is known living from a number of localities in Michigan, and from Maine, New York, and Michigan in marl beds (Baker, 1911, pp. 290–91, pl. 32, figs. 15–22). It is apparently a Pleistocene species that is dying out, being characteristic of the cold climate immediately following the retreat of the ice.

SANGAMON RIVER, NEAR MAHOMET

The mollusks from this locality occur in a sand stratum four feet below the surface. The fauna is distinctively of a fluviatile character and not of pond character, as is the case with the Urbana marl fauna. The species obtained by Dr. Savage are listed below:

UNIONIDAE

Fragments of a river mussel.

SPHAERIIDAE

Sphaerium solidulum (Prime)

Apparently rare. Found throughout the state.

Pisidium compressum Prime

A half-valve of this common Illinois species was found. It evidently drifted from a more favorable habitat.

Viviparidae

Ambloxis integra (DeKay)

A post-embryonic individual and two half-grown individuals occurred in the collection. It is a common *Campelona* (=*Ambloxis*) in Illinois.

Valvatidae

Valvata tricarinata (Say)

Apparently a rare species in this deposit.

Amnicolidae

Amnicola limosa porata (Say)

One broken shell of this common *Amnicola* was noted in the collection.

Pleuroceridae

Pleurocera elevatum (Say)

This common river snail is very abundant in these deposits and includes the typical form together with individuals showing spiral lines on the base of the shell, indicating a tendency to vary toward the race known as *lewisii*. In some individuals the growth lines near the aperture are raised to form costae. All ages are represented, and the young are strongly carinate. *Elevatum* is distributed throughout the state.

Planorbidae

Planorbis antrosus Conrad (=*bicarinatus* Say)

Three specimens of this widely distributed species were observed in the collection. The single adult individual is small for the species.

Endodontidae

Pyramidula solitaria (Say)

A single broken shell of this species of land snail was found with the fresh-water species, evidently a stray individual which had fallen or been washed into the stream.

SANGAMON RIVER, BELOW MAHOMET

About three-quarters of a mile below Mahomet, on the north bank of the Sangamon River at the first bend below the second bridge, a sand stratum occurs in a section of the river bank on the old flood plain. The stratum is about 2 inches in thickness and lies from 8 to 12 inches below the surface of the river terrace and about 5 feet above the level of the river, the latter being rather high for the season (July). The deposit can be traced for over a hundred feet in the bank. Its extent in the terrace could not be ascertained, but it is apparently considerable. At one place it disappeared beneath a large tree stump over two feet in diameter, indicating that the deposit antedated the present forest. The terrace here appears to be above the influence of the highest water, and it is evident that the deposit is post-glacial and was laid down before the Sangamon had cut its bed to the present depth. It possibly represents the flood plain of an earlier Sangamon.

It will be noted that this deposit is at a higher level than the one examined by Dr. Savage, and is probably younger. Of the species obtained from the higher level, 8 are different from those collected by Savage, and 4 species are included in the Savage collection that are not in the Baker collection. *Pleurocera elevatum* occurs in both collections and is still living in the Sangamon River. In both fossil deposits it is very variable in the degree of spiral ornamentation, varying, perhaps, more than the recent shells of the Sangamon. *Ambloxis integrum* is fairly common at the higher level deposit but rarer at the level from which Dr. Savage collected his specimens. This species lives in the Sangamon in large numbers but has not as long a spire as the fossil individuals.

The surface of the flood plain of the Sangamon River near the first bridge below Mahomet is covered with dead, bleached shells of mollusks, of the same species, mostly, as those found in the deposit examined lower down the river, but they are mixed more or less with recent shells from the river and their age and stratigraphic relation cannot be definitely determined. No deposit comparable to that found in the bend of the river below Mahomet was observed here, though the river bank was carefully examined for a

considerable distance. It is not safe to list such material, and it has therefore been ignored.

The list of mollusks obtained from the high-level deposit is as follows:

SPHAERIIDAE

Sphaerium sulcatum (Lamarck)

Rare, only a half-valve was found.

Sphaerium stamineum (Conrad)

Not abundant, 7 valves included in the collection.

Sphaerium solidulum (Prime)

A half-valve is doubtfully referred to this species by Dr. Sterki. It is broken, but is apparently the same as the shells from the lower deposit referred to this species by Sterki.

Pisidium virginicum (Gmelin)

A half-valve of this large *Pisidium* was found. It is common as a Pleistocene fossil and as a recent mollusk in Illinois.

Pisidium compressum illinoisense Sterki

Three valves. The presence of this recently described Pisidium in this Pleistocene deposit is of interest. It lives in a reservoir and pond in Washington County, near Dubois, and in Sheller Lake, Jefferson County, in great numbers, obtained by the veteran Illinois collector, Mr. A. A. Hinkley. Of the species Sterki says (1916, p. 448), "All are of the same shape, differing somewhat in size and color, but remarkably uniform in each habitat. It is a peculiar form, having almost the significance of a species." Typical *compressum* was the only form of this genus found in the material collected by Dr. Savage.

VIVIPARIDAE

Ambloxis integra (DeKay)[1]

This large snail occurs in the deposit in considerable numbers; the majority of the individuals, however, are young or half-grown. The adult shells are unlike any figured in the monographs, resembling most nearly Haldeman's figure 2 of his monograph, but with

[1] See Pilsbry, *Nautilus*, XXX, pp. 109–14, 1917, for the reasons for the change of generic name from *Campeloma*.

a longer spire and deeper sutures. There are seven full whorls in the largest fossil specimen, which measures as follows: Length, 40; breadth, 22; aperture length, 20; breadth, 12 mm.

Integra is widely distributed in Illinois but has been confounded with *subsolida* and *decisa*, from both of which it differs notably.

Valvatidae

Valvata bicarinata Lea

Not common.

Amnicolidae

Amnicola limosa (Say)

Two shells of this species were observed in the loose sand taken from the aperture of Ambloxis.

Pleuroceridae

Pleurocera elevatum (Say)

As in the deposit examined by Dr. Savage, this species is the dominant mollusk in the deposits examined by the writer, and the shells exhibit the same range of variation as do those from the lower stratum. Several individuals are smooth without indication of spiral liration and every degree of ornamentation is represented to shells with a heavy, keel-like carina on the periphery. This species is abundant, living in the Sangamon River, where it is equally variable.

Planorbidae

Planorbis antrosus Conrad

Rather common, but the individuals are smaller than normal.

Planorbis campanulatus Say

One adult shell of this species was found in the collection.

Endodontidae

Pyramidula alternata (Say)

Several shells of this common land mollusk were collected from the deposit, indicating that this wood snail has lived in this vicinity for a long time. It was not found in the lower deposit but a related species, *Pyramidula solitaria*, occurred.

TABLE II

Relation of Molluscan Species to the Two Deposits on the Sangamon River

	Savage	Baker	Now Living in River*
Sphaerium sulcatum	....	*x*	....
Sphaerium striatinum	....	*x*	....
Sphaerium solidulum	*x*	*x*	....
Pisidium virginicum	....	*x*	....
Pisidium compressum	*x*	....	....
Pisidium compressum illinoisense	....	*x*	....
Ambloxis integra	*x*	*x*	*x*
Valvata tricarinata	*x*	....	....
Valvata bicarinata	....	*x*	....
Amnicola limosa	....	*x*	....
Amnicola limosa porata	*x*	....	....
Pleurocera elevatum	*x*	*x*	*x*
Planorbis antrosus	*x*	*x*	....
Planorbis campanulatus	....	*x*	....
Pyramidula alternata	....	*x*	*x*
Pyramidula solitaria	*x*	....	....

* Some of these species may be found living in the Sangamon or its vicinity.

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SAMUEL WENDELL WILLISTON
1852–1918

Our distinguished senior colleague in vertebrate paleontology passed away August 30, 1918, honored and beloved by all who knew him. He seldom spoke of himself, still less of the long struggles which beset his career. Our admiration for his character and attainments is enhanced through the perusal of his personal recollections,[1] which reveal a lofty spirit and an unfaltering determination. In the opening pages of his reminiscences he writes:

> As the oldest living student of vertebrate fossils in America and one of the oldest in the world, friends have urged me to write some of my recollections. Not that I am so very old, but because there were so few vertebrate paleontologists in the days when I first became interested in the subject—only Leidy, Cope, Marsh, and a few other lesser lights in America. Nor were there more than a dozen others in all the world, of whom Sir Richard Owen was the chief, who had published much about extinct vertebrates. It has never seemed to me that there was much of interest that I could say about myself, nor very much about the pioneers in paleontology that I could tell. I begin to feel that there are not many more years of work before me, and to regret that I have not accomplished more. . . . . But the way has often been hard, and I am thankful to be spared so long and to have done what I have.

And again, in closing:

> My life, as I look back on it, has had many discouragements and many pleasures. I have made many mistakes, as I now can see, and I have not

[1] See *Recollections*, an unpublished autobiography, written May, 1916, copyrighted by Mrs. S. W. Williston.

accomplished what I might have done. If I may extenuate my views I will say that for a country boy, with but little help and wholly without influence, the road to success is very hard. . . . . Perhaps for me experience was the best teacher, and an easy path in youth might have caused failure. But it was hard, and I have more than once been discouraged. I have drifted along somehow, with one underlying ambition, to *learn.* My plans and ambitions may seem fickle, first as an engineer, next as a physician, as a chemist, entomologist, paleontologist. I have tried various things, when one of them steadily pursued would have been better. In reality there was only one ambition—*to do research work in science.* And I have realized that ambition in a measure. I have published about 300 books and papers totaling about 4,000 pages. But the chief satisfaction that I find now in looking back over my life is that I have been the means, to some extent at least, of assisting not a few young men to success in medicine and in science.

Like all men of science who have risen to distinction, Williston was self-made, the impulses all coming from within; yet he was instinctively alert to seize every chance to learn and to expand his horizon. We cannot imagine a life-story more helpful than his to the youth predisposed to science who has both to discover his own talent and to explore every avenue of opportunity which presents itself.

Williston was born in Roxbury, now a part of Boston, July 10, 1852. "The Williston family," he writes, "has been traced back to about 1650 in Massachusetts; they were about the usual run of common people, no one famous or even noted, whether for good or evil. . . . . Some of them served in the War of the Revolution, and many were fishermen." His father was born in Maine, and he remarks of this branch of the family that "they knew little of schools. My father, if he ever went to school, did not take kindly to study, for he never learned to read or write. . . . . It was a great pity, too, for my father was a man of far more than ordinary ability as a mechanic—he was noted always for his skill. . . . . Of all his children I resembled him the most, both physically and mentally." His mother was from England, having come with her parents to New Jersey about 1812. She had a fair common-school education, and the effects of her early English training and her accent remained through life.

In the small garden attached to the little frame house in Roxbury began Williston's first studies in natural history, at the age of four:

My father had a little garden. He was planting potatoes one day with my aid, when several toads were unearthed. I was very curious to know where they came from, and he told me that they grew in the ground. I puzzled my childish brain about them and determined to raise a crop of them myself, so the next day I sedulously collected all the small toads I could find, in my little apron, and proceeded to plant them as I had seen my father plant potatoes. My father observed me and asked what I was doing. I told him I was planting them to see them grow. It caused him so much amusement that I went away crying to tell my mother about it. For years, until I was so old that I resented it, my father always called me "Toad."

The double point of this batrachian incident lies in its indication of an experimental mind, and in the coincidence that forty-one years later Williston succeeded Cope as one of the leading world-students of the extinct batrachian group.

The intellectual and social environment of Roxbury probably never would have produced a geologist or a paleontologist, and while the next step in Williston's life was hard, yet it was propitious, as the events proved:

In the spring of 1857 my parents decided to emigrate to Kansas. A colony had left the year before for Manhattan, and the letters that came back had infected many with the desire to go West. . . . . The abolitionists were urging eastern people to colonize the territory in order to help John Brown preserve it to the "Free States." . . . . The trip was long and tedious, by rail to St. Louis, then a small place, and thence by steamboat up the Missouri River to Leavenworth. There was no Kansas City then. We reached Leavenworth about the twentieth of May. Here we remained a few days in a very small hotel, while my father bought a yoke of oxen and a wagon and such provisions and household things as were indispensable, and we started on the slow and tedious drive of 115 miles to Manhattan through a country but very sparsely settled. For the most part we children rode in the covered wagon, while my father and cousin walked and drove the oxen. My mother was very homesick on the way. I can remember how long and bitterly she cried. One could not blame her; she now realized for the first time in this wilderness what she was leaving behind, perhaps forever. Nor did she see the East again for nearly thirty years, and my father never. We reached Manhattan June 7. The Emigrant Aid Society, under whose auspices this long journey was undertaken, provided a small log cabin, about 15 feet square inside, two and a half miles east of Manhattan, for our temporary use until a house could be built in the town itself. My memory of events is now becoming clearer. The house of our temporary occupation had but a single room with a loft reached by a ladder. There were two beds in the room below, screened off by cloth curtains that my mother soon found for them, and we

four boys slept in the loft. A big fireplace in one end, used for cooking, and a rough table and a few chairs comprised the furniture. I do not wonder that my mother was despondent, for there were no neighbors within two miles, and she needed courage, for the Potawatomie Indians had a village in the immediate vicinity, and the word Indian in the East was a synonym of savage. . . . . Like most Indians, they were thieves and unreliable, but I do not suppose we were in much danger for our lives. . . .

With these New England instincts, almost the first building erected in the village was a stone schoolhouse in the western part of town. It was of two stories, the first of which was never completed and served as a fine playhouse for the younger children. The second floor, in a single room twenty by thirty in size, was where my early education was obtained as far as algebra and McGuffey's fifth reader. My mother took the *Boston Free Flag*, a semi-literary paper, and there were a few books in the town the first winter I spent in it. Among other gifts of the Emigrant Aid Society to this colony was a small library of a few hundred volumes of more standard books, but I did not find a great deal in it to interest me. They were too mature for my childish comprehension. One only I recall, Stevens' *Antiquities of Central America.* I read it when I was about seven years old, and although I have not seen the work for many years I can still vividly visualize its many pictures of Aztec ruins in Yucatan. It directed my interest to Tschudi's *Peru* and Prescott's *Conquest of Mexico*, which a few years later made a deep impression on me and gave me that fondness for history which formed a large part of my reading for the next ten years. The Sunday-school libraries were soon exhausted, as I would take home every Sunday all that the teachers would permit. One only I can recall, Adoniram Judson's *History of His Missionary Experiences in Tahiti.*

Another incident of my seventh year stands out vividly in my recollections. Just north of Manhattan is Blue Mont, a steep and high bluff, the termination of a range of hills ending abruptly in the Blue River. In the sand bars of the river we boys often gathered clams, and I was surprised to find on the summit of Blue Mont shells which looked much like clamshells. I asked my father how they had got to the top of the bluff on the rocks, for all the clams I had seen lived in the water and could not crawl on land. He told me they had been left there by the great deluge which once covered all the earth. I took some of the shells to my Sunday-school teacher and she told me the same, and so Genesis acquired a new interest for me, and most of the verses I was required to memorize each week from the Bible were chosen from the Old Testament. My mother had prohibited us boys from going to Blue Mont and the river, for like most mothers she was afraid of the water, and not until I had surreptitiously learned to swim did she consent to let me go in swimming. Our favorite swimming-hole was among large stones filled with fossil shells of lower Permian age, and they were my first studies in paleontology. The old cottonwood house was too cold and inhospitable for our large family, and in 1859

my father built a better house about a quarter of a mile away. It was two full stories in height, and twenty by thirty, a large house then for the village. It was built chiefly of black walnut lumber, sawed by the little "Emigrant Aid" sawmill, and was long known as the "Black Walnut House." Its shingles and floors were of pine, brought up the Kaw River on a steamboat, one of the three that ever went so far up the river. I remember especially the boat, because its name in large letters spelled to me "Col-o-nel Something," and it worried me not a little that everyone persisted in calling it "Kernal." The pronunciation of the English language was a very mysterious and incomprehensible thing to me in those days.

We had been in this home but a very short time, not long enough to get settled, when there came up one evening one of those "cyclones" for which Kansas was long notorious. It threatened to blow down the house, and did destroy the house from which we had just moved, distributing some of its lumber quite into our back yard. . . . .

In 1860 my father bought the "Emigrant Aid Saw and Grist Mill." . . . . This was the year of the great drought, when practically no rain fell for fifteen months, and the crops were almost a total failure. Our subsistence for many months was almost exclusively corn meal and sorghum. There was no coffee except barley coffee, no tea, and no sugar. I have never been fond of corn bread since that time. When after more than a year my father obtained a sack of flour, the biscuits that my mother baked linger in my mind as the greatest delicacy and luxury of my life. . . . .

It was during this time that I got my second lesson in natural history. My father was very fond of fishing and hunting and went fishing every Sunday in the Blue River. Among the fishes that he brought home, chiefly catfish, shad, and buffalo, were river sturgeons. I usually helped him clean and prepare them for cooking. I observed that the sturgeons had no backbone like the other fishes, but instead, a long fibrous rod, the notochord. I puzzled greatly over it, but no one could give me any enlightenment. It was one of the things that later directed my interest to natural history.

Blue Mont College, founded by the Methodists in 1859, became merged into the State Agricultural College in 1864, and I was a very happy boy when in 1866 I was permitted to enter it.

Williston was now fourteen years of age, but it was not until a year later that he came under the influence of real scholarship and of a truly great work of science:

It was about this time, when I was fifteen years old, that Professor Mudge loaned me Lyell's *Antiquity of Man*. I remember the night I brought it home there was a dance at our house, in which I was not included, but it gave me the opportunity in an upstairs room to read the book until the guests departed in early daylight hours. I was thoroughly convinced, when conviction meant

antagonism to the church's teachings. Professor Mudge lectured about this time on evolution, to which he remained opposed until his death. It was my first introduction to the doctrine to which I soon after became a devoted disciple. . . . .

I was very fortunate in the character of my teachers, especially the teacher of science, Professor Mudge. I have published a brief sketch of his life and need not say more about him here. I doubt not that my life has been devoted to natural science chiefly because of his influence. I studied every study that he taught and they were many: natural philosophy, chemistry, botany, geology, zoölogy, veterinary science, mineralogy, surveying, spherical geometry, conic sections, calculus, etc. Mudge had a considerable collection of fossils and minerals that filled a long case. To me it was a wonderful museum. There were no laboratories of any kind, no microscopes, and but few instruments. The college catalogue of about that time, in enumerating its equipment, gravely mentions an electric machine, three Leyden jars, and six test tubes. The electric machine was a never-ending source of delight. The Professor occasionally got it out and charged the Leyden jars, and then, with hands joined in a circle, gave us a shock. He prophesied that some day electric light would take the place of other illuminations. My ambition was to make a machine myself, and I nearly succeeded, but I found no way of boring a hole through the glass plate for the shaft. The oxyhydrogen light was another great wonder. My greatest interest was given to physics, or natural philosophy as it was then called. I read every book on the subject that I could get in the library. Chemistry had second place, while biology interested me but little.

Williston left home at the age of seventeen, adventuring life first as a day laborer and then as a railroad engineer's assistant. He returned, however, to the Kansas Agricultural College and took the degree of B.S. in March, 1872. Once again he took up civil engineering, which he followed for a year. It was this profession that prepared him for his field work and for his subsequent observations in geology. It was in the spring of 1873 that he undertook the study of medicine in the office of his old family physician. Here he had free access to the doctor's library, and he at once turned to his initial studies in anatomy and physiology, which laid the foundation of his anatomical training and ultimately qualified him for a professorship in the medical school of Yale University.

In the meantime he had become an enthusiastic follower of the Darwinian doctrine, which was not at that time accepted as a demonstrated fact, and in February, 1874, he delivered in the local

Congregational church what he believed to have been the first public lecture in favor of evolution given west of the Mississippi River.

Quite by accident Williston accepted an invitation from a fellow-student to accompany him to northwestern Kansas (Smoky Hill Valley), where Professor Mudge, already famous through his discovery in 1872 of the specimen of *Ichthyornis*, was collecting. He writes:

> We left on the fifth [July, 1874]. *It was this accidental and thoughtless decision that led to my life's devotion to paleontology.* Had I not gone with him, in all probability I would today have been a practitioner of medicine somewhere in Kansas. We joined Mudge about the fourteenth and started almost immediately south. In a few days I found a good specimen of pterodactyl and became an enthusiastic lover of the sport of collecting fossils—for sport it seemed to me. I had planned that autumn to go East, if I could borrow a couple of hundred dollars, to attend a medical college. And so I returned to Manhattan by rail in September but did not succeed in getting the necessary funds. Mudge thereupon asked me to return, which I did about the first of October, and remained until we returned in November. . . . . For my season's work Mudge paid me $25, which bought me a suit of clothes and other things badly needed. My total cash income this year was not more than $50. It was the hardest year of my life. My board I worked for in part, in part I had it paid for by my parents, but I did not have a second whole shirt, and when I gave my address I had to borrow clothes to wear, for my clothes were ragged and patched.
>
> Times now began to improve. Professor Marsh and Professor Cope, as is well known, were rivals and very jealous of each other. They had been quarreling with each other for two or three years, with mutual criminations and recriminations. Because of the discoveries Marsh was making in the Cretaceous of Kansas, Cope grew eager to participate in them but could find no one to undertake these collections, for Marsh was afraid to have too many learn about the region for fear that Cope would seduce some of the assistants by the offer of higher pay. He therefore instructed Mudge to retain his assistants of the previous summer. Brous and I were engaged for the following season at $35 a month and our expenses. We accepted the offer gladly and started for the field overland in early March, meeting Mudge at Ellis on the railroad. We stipulated that I should quit in September to allow medical lectures. . . . .
>
> We collected chiefly along the Smoky Hill Valley that season, as far west as Fort Wallace, and got many valuable specimens. . . . . By Marsh's directions each had signed his name to the specimens he had collected. Perhaps that was the reason he invited me in February to come to New Haven. I

promptly accepted his invitation and sold my watch and borrowed enough to take me there in March. . . . . It was thus with feelings almost of awe that I met Professor Marsh for the first time at New Haven, Connecticut, on March 19 or 20, 1876. My heart was in my mouth when I knocked at the basement door of the old Treasury Building and heard the not very pleasant invitation to "come in." There was a frown on Marsh's face, accentuated by his nearsightedness, as he waited for me to state my business. No doubt he thought me a wild and woolly westerner in my military cloak, slouch hat, and cowboy boots, as I stammered my name. But he quickly made me feel more at ease. He found me quarters in a little building in the rear of Peabody Museum then approaching completion. The next day he set me at work studying bird skeletons with Owen's *Comparative Anatomy* as a guide. He was then deeply interested in his Odontornithes, and wanted newer specimens, especially of the smaller forms, which were very difficult to find in the Kansas chalk. For recreation I helped a few hours every day to carry trays of fossils to the museum.

Williston was now twenty-four years of age. Vertebrate paleontology had become his first love, but he had leanings toward human anatomy and medicine and entomology, first as an avocation and then as a vocation. He was afforded no independent opportunities for paleontological research and publication by Professor Marsh. In the summer seasons of 1876 and 1877 he collected with Professor Mudge in the Cretaceous chalk of Kansas. In 1877 he was sent by Professor Marsh to the Morrison, Canyon City, and Como quarries to co-operate with Professors Lakes and Mudge and Mr. Reed in taking out the types of *Atlantosaurus*, *Diplodocus*, and other sauropods. In Professor Marsh's laboratory Williston worked on the dinosaurs. In the field in 1878 he helped to collect the "Jurassic Mammals" and some of the smaller dinosaurs. For nine years (1876–85) he worked in Professor Marsh's laboratory, where he became closely associated with Marsh's other assistants, especially Harger and Baur, who influenced him greatly and for whom he had great admiration. He wrote a biographic note on Harger in 1887, which gives some interesting side lights on the relations of Professor Marsh to his assistants. In 1878 he published a brief communication on American Jurassic dinosaurs in the *Transactions* of the Kansas Academy of Sciences; but he had very little opportunity for further publication in vertebrate paleon-

tology as long as he was in New Haven. This led to the renewal of his medical studies.

While acting as assistant in paleontology he studied medicine at Yale, received the degree of M.D. in 1880, continued his post-graduate studies, and received the degree of Ph.D. at Yale in 1885. He then became demonstrator of anatomy (1885–86) and professor of anatomy (1886–90) at Yale and practiced medicine in New Haven, where he was health officer in 1888–90.

In 1886 he published some criticisms of Koken's work on *Ornithocheirus hilsensis* which give us some hint of his abiding interest in Kansas fossil reptiles, an interest which was soon to bring great results.

The turning-point in his scientific career, from anatomy and medicine to paleontology, came at the age of thirty-eight, when he returned to the University of Kansas as professor of geology. Kansas was the scene of his first inspiration in paleontology, and here his fossil studies and vigorous health marked the happiest period of his life. He taught both vertebrate and invertebrate paleontology, anatomy, and medicine, and several of his students have achieved distinction in these fields.[1] With respect to the breadth of his studies and of his influence at this time, his life was comparable only to that of Joseph Leidy, who, it will be recalled, was at once an anatomist, a physician, a paleontologist, and a microscopist of distinction. He soon began to publish studies on the Cretaceous reptiles of Kansas. Henceforth Kansas plesiosaurs and turtles, mosasaurs and pterodactyls, were the subjects of a long list of papers, mostly in the *Kansas University Quarterly*, from 1890 to 1899, with occasional articles on Kansas fossil mammals (*Platygonus*, *Aceratherium*, *Teleoceras fossiger*). Meanwhile he made many explorations of the Cretaceous of Kansas for fossil reptiles. At Kansas University Williston also kept up his two avocations of anatomy and dipterology; he served as professor of anatomy and dean of the medical school. He also continued to publish many papers on recent Diptera.

[1] Among these paleontologic students, who have since become known for their researches, were: E. C. Case, C. E. McClung, Roy L. Moodie, Herman Douthitt, Alban Stewart, Elmer S. Riggs, Barnum Brown, M. G. Mehl, and E. H. Sellards.

WORK ON THE DIPTERA

We may for a moment divert our attention to Williston's great work on the Diptera. At the Pittsburgh meeting of the Entomological Society of America in 1917 he gave many interesting reminiscences of his early work; he showed that he turned to the Diptera when he despaired of securing original material in vertebrate paleontology. It is seldom that science has seen talent so evenly divided between subjects so remote as dinosaurs and flies.

J. M. Aldrich, in his *Catalogue of North American Diptera* (Smithsonian Miscellaneous Collections, 1905), cites sixty-seven titles by Williston, covering the period from 1879 t9 1899, and adds this note:

> An admirable feature of Williston's work, which does not show fairly in the above list, is the attention he has given to identifying and redescribing the species of other writers. In all his longer papers this is a prominent part, frequently occupying as much space as the new descriptions, and requiring more time than they in preparation.

This feature of Williston's work was, in fact, the result of his ever-active desire to be helpful—the same desire which prompted him to prepare his *Manual of North American Diptera*, a book which is indispensable to a beginner in dipterology and a very great convenience to advanced workers. It was this kindly, sympathetic spirit too which endeared him to his students and fellow-entomologists, while his accurate observations and keen judgment commanded respect everywhere.

Williston practically ceased active work on flies twenty years before his death, although his interest in them continued, as was shown by occasional papers, especially from 1906 to 1908 and again in the later years of his life. He jokingly said in conversation that he did not dare to think of flies lest he be tempted to take too much time from fossils. His collection of Diptera from the United States and Canada is now in the University of Kansas; the remainder of his collection, including much of the valuable material which he had collected while writing the volumes on Diptera in the *Biologia Centrali-Americana*, is in the American Museum of Natural History.

PALEONTOLOGIC WORK IN KANSAS[1]

Williston's paleontologic contributions on the Cretaceous fauna of Kansas began in 1879 with a short paper entitled "Are Birds Derived from Dinosaurs," and included fifty-three communications, chiefly to the Kansas Academy of Science, the *Kansas University Quarterly*, and the University Geological Survey of Kansas; also three volumes on the *Cretaceous Fishes* in co-operation with Alban Stewart; and *Paleontology* (*Upper Cretaceous*), Part I, Volume IV of the University Geological Survey, which was chiefly prepared by Williston with the assistance of his students Adams, Case, and McClung, and is a thorough review of the geology and marine fauna of the Cretaceous seas, containing the first clear distinctions and restorations of the great Kansas mosasaurs, *Clidastes*, *Platecarpus*, and *Tylosaurus*. This work became the standard for all subsequent researches of Osborn, Wieland, and others on the Cretaceous fauna. It contains some admirable restorations of mosasaurs and other fossils which may be compared with those of Dollo from the Maestrichtian of Belgium. The second part, Volume VI of the University Geological Survey, covering the Carboniferous and Cretaceous, published in 1900, included the Cretaceous fishes alluded to above, and the Carboniferous invertebrates by Joshua W. Beede.

In 1897 Williston published his first paper on Paleozoic tetrapods, a brief description of "A New Labyrinthodont from the Kansas Carboniferous"; his second was on the "Coraco-Scapula of Eryops Cope" in 1899; but nearly a decade elapsed before the Paleozoic reptiles and amphibians became his chief subject. From 1897 to 1902 he was engaged chiefly upon his series of papers on fossil vertebrates of Kansas for the University Geological Survey of Kansas.

Williston concluded his studies of the Cretaceous fauna during the early years of his professorship in Chicago, beginning in 1902. Thus his work on the Kansas Cretaceous fauna, following the very disjointed contributions of Leidy, Marsh, and Cope based on

[1] These notes on Williston's work on fossil reptiles and amphibians have been prepared in collaboration with Professor W. K. Gregory, of the American Museum of Natural History.

inferior material, marks the turning-point in this field to the new order of description and generalization based upon complete material, including even the skin impressions of several great mosasaurs. In his observations on the mosasaurs, plesiosaurs, pterodactyls and marine turtles, and the birds with teeth, Odontornithes, he placed the osteology of these several animals on a much more secure basis, adding a number of new generic types, such as a short-necked plesiosaur, *Dolichorhynchops osborni*.

His interpretation of function and habit is shown in his restorations of all these types, and his first observations on the feeding habits of the plesiosaurs and his more mature views on several of these animals were published during his sojourn in the University of Chicago, namely, "Relationships and Habits of the Mosasaurs," *Journal of Geology*, 1904; "North American Plesiosaurs," 1903, 1906, 1907. His first contribution to the phylogeny and classification of the Reptilia as a whole appeared in 1905 and was followed by his important discussion of this subject entitled "The Phylogeny and Classification of Reptiles," *Journal of Geology*, August, 1917. In this article, which expresses his mature opinions, he departed from his previous conservative attitude toward classification and proposed to add two subclasses of reptiles, the Anapsida and Parapsida, to the subclasses previously proposed by Osborn, namely the Synapsida and the Diapsida, making a fourfold grand division of the Reptilia. Doubtless it was Williston's intention to fortify this system of classification in his forthcoming general work on the Reptilia.

WORK ON PRIMITIVE AMPHIBIANS AND REPTILES[1]

In 1902, at the age of fifty, Williston was called to the University of Chicago as head of the new department of vertebrate paleontology, a chair which he occupied with great distinction and with continued influence for the remaining sixteen years of his life. He now began to concentrate his attention more exclusively on vertebrate paleontology. During the first six years he continued his studies and publications on the Cretaceous reptiles; then he began to turn toward the study of far more difficult and obscure problems, namely the relatively primitive amphibians and reptilian life of the

[1] See footnote, p. 683.

Permian, where in several groups he marked the beginnings of the higher forms which he had previously studied, as well as the adaptive radiation of the lower forms to a great variety of habits and habitats.

Professor E. C. Case, now of the University of Michigan, who was one of Williston's students at the University of Kansas, had co-operated with the late Professor Georg Baur at the University of Chicago in the study of *Dimetrodon* and other Permian reptiles and had collected for that University a number of important types of pelycosaurs and cotylosaurs. After Baur's untimely death Case continued to collect and study the Permian reptiles and amphibians of Texas and other states, finally issuing his well-known Carnegie Institution monographic revisions of the Pelycosauria and Cotylosauria, in which he revised and extended Cope's work on these animals and figured the types and other important specimens in the American Museum of Natural History, in the University of Chicago, and elsewhere. Thus Cope, Baur, Case, and Broili had opened and partly explored an important field of work which Williston had long desired to enter.

Accordingly in 1907 and 1908 Williston began to publish on this subject which occupied most of the closing decade of his life and constituted perhaps his greatest contribution to science. It is pleasant to record that Williston and Case at all times fully and cordially co-operated with each other in the study of Permian reptiles and amphibians. In 1908 he published an important but brief paper on the Cotylosauria, containing a description of the skeleton of *Labidosaurus incisivus*. In the same year Mr. Paul C. Miller, of the American Museum of Natural History, a collector and preparator of high rank, became Professor Williston's assistant at Chicago, and under his direction began a long series of explorations in the Texas Permian which have yielded results of the greatest importance to vertebrate morphology and paleontology. During the next decade these expeditions brought back to the University a great number of specimens, some of which will become more and more famous as their great importance is gradually realized. More or less complete skeletons were discovered, extricated with great skill, and admirably described in a long series of publications.

Among the more important of the new or little-known skeletons were the following, which, to students of the early evolution of the skeleton of vertebrates, will ever stand as important types:

Pariotichus laticeps, Williston
Trematops milleri, Williston
Aræoscelis gracilis, Williston
Seymouria baylorensis, Broili
Casea broilii, Williston
Mycterosaurus longiceps, Williston
Trimerorhachis insignis, Cope
Varanosaurus brevirostris, Williston
Ophiacodon mirus, Marsh

These were only the more conspicuous of the many priceless specimens which Williston and Miller have brought to light, and which the former has described and figured with the most painstaking care and accuracy. This material also enabled Williston to give definite and in many cases final figures of the sutural limits of the elements of the skull in most of these genera. Many investigators had attempted to do this from less extensive and complete material, but their results were often uncertain in detail and subject to important changes and corrections.

In 1911 he published from the University of Chicago Press his volume, *American Permian Vertebrates*, which comprises a series of monographic studies on some of the genera already noted. This work contains many new and original plates. Careful and extensive definitions are given of the orders Temnospondyla, Cotylosauria, Theromorpha, and of the included families and genera. In the same year, by invitation of Professor Schuchert, Williston examined and described the important collection of Permian reptiles which Mr. Baldwin had collected for Professor Marsh between 1877 and 1880, but which had never been thoroughly studied. Among other important results of this research was the erection of a new family of Cotylosaurs, the Limnoscelidæ, to include the skeleton of *Limnoscelis paludis* Williston. In 1912 he published, in collaboration with Professor Case, a paper on the "Permo-Carboniferous of Northern New Mexico," in the *Journal of Geology;* he also published a general review of primitive reptiles in the *Journal of Morphology*. In 1913 appeared a memoir in collaboration with Case and Mehl

on *Permo-Carboniferous Vertebrates from New Mexico.* The same year saw the publication of his important papers on the primitive structure of the mandible in amphibians and reptiles and on the skulls of *Arœoscelis* and *Casea.* The close resemblance of *Arœoscelis* to the Squamata especially in the temporal region was noted.

Early in 1914 came the publication on *Broiliellus*, one of Cope's "batrachian armadillos," and the fuller description of the osteology of *Arœoscelis*, with a discussion of the relationships of *Arœoscelis*, the Protorosauria, and the Squamata. He then referred *Arœoscelis* to the Protorosauria and placed this order next to the Squamata. In the same year he published a series of life-restorations of some American Permo-Carboniferous reptiles and amphibians.

His principal publication in 1914 was the book on *Water Reptiles of the Past and Present*, in which his life-work on these animals was admirably combined with the results obtained by other workers. Williston had shown a bent for the harmonious study of form and function, of structure and habit, of environment and adaptation, which he applied with skill and originality to the interpretation of the highly diversified forms of aquatic life. He followed Eberhard Fraas, of Stuttgart, in making a special study of aquatic adaptations in the vertebrates; consequently his book on the water reptiles constitutes one of the most important contributions which we have upon this subject.

The year 1915 produced his papers on *Mycterosaurus*, a very interesting reptile, that threw light on the origin of the diapsid types, namely of reptiles with *two* arches at the side of the temporal region of the skull. Also on *Trimerorhachis*, perhaps the most archaic of the American Temnospondyls, or amphibia with the vertebrae composed of several pieces. In 1916 he published the careful description of the skull and skeleton of *Pantylus* and of *Theropleura*, together with the important discussion of the origin of the mammalian and reptilian types of sternum. This paper was followed by the admirable *Synopsis of the American Permo-Carboniferous Tetrapoda*, in which the principal types were illustrated, and careful definitions of the various groups were given. In 1917 he began a general work on the *Reptiles of the World, Recent and Fossil*, upon which he was actively engaged up to his

last illness; also the publication of his papers on *Edaphosaurus*, on the atlas-axis complex of reptiles, and, equally important, his brief paper on the "Phylogeny and Classification of Reptiles," previously mentioned. During the last two years of his life he was also preparing a paper on new Permian reptiles.

In summing up his life-work, "I like," says Doctor Gregory[1], "to emphasize the general features in which Williston was really preeminent, namely: (1) discovery of new material, Cretaceous Reptilia, Permian Tetrapoda, and Diptera; (2) conscientious and precise description of these; (3) eminently conservative synthesis of facts so as to work out a great and enduring record of Cretaceous and Permian reptiles; (4) intensive and successful specialization in several distinct lines of research and teaching.

It is a matter of the deepest regret to all of Williston's colleagues in paleontology that he did not live to complete his great comparative work on the Reptilia, which would have summed up all his researches and observations and the facts stored in his mind which have never found their way into print. As an investigator he combined in an exceptional degree anatomic accuracy in detail with breadth of vision and power of analysis. His associates in the special field of Permian research considered his opinion as a homologist weighty. A committee was formed, chiefly composed of Americans, of which Williston was senior, to endeavor to establish the difficult and intricate questions of homology and to base upon this an enduring terminology to replace the confusing whirlpool of names for certain skull bones which have accumulated since the time of Cuvier.

A few of the more general features of Williston's life-work and character are as follows: He strove arduously through forty years of investigation to discover new material in the field and to widen our basis of facts in several distinct lines of investigation; he preferred to discover new facts rather than to reinterpret older ones or to adjust the interrelations of facts; in general, his material was notably of his own finding. Nevertheless, especially in his late years, he labored very successfully to classify and synthetize his material, and with it that which had been treated by other workers.

[1] See footnote, p. 683.

Here his genial personal character and admirable relations with his colleagues shone forth; he was singularly appreciative of the work of other men and ready to adopt whatever he believed to be solid and enduring in previous attempts at classification. Thus Williston's work stands in contrast with that of Cope and Marsh, whose personal differences of opinion led to the setting up of two entirely distinct systems of classification as well as of nomenclature, irrespective both of priority and of merit.

Williston's keen, broad knowledge of human anatomy, of the muscles as well as of the bones, doubtless aided his penetrating insight into the habits of the extinct animals, and while generally conservative and cautious his phylogenetic studies and suggestions were of high value. His views on taxonomic standards[1] and upon college and high-school education[2] were, like his views upon paleontologic problems, characteristically sober, moderate, and well considered, lighted up in their expression with his genial, half-humorous manner. He was ready to confess and appraise defects or faults on his own side, but quick to resent exaggerated accusations and criticisms from the other side.

The closing years of Doctor Williston's life were clouded by illness and the sorrow of losing a much-beloved daughter. He was a devoted husband and father. His friends and colleagues met him last at the Pittsburgh meeting of the Paleontological Society of America, December 30, 1917, and enjoyed a few of his short and characteristically enthusiastic communications and discussions. With Doctor Holland, myself, and many other warm friends he stayed the Old Year out and saw the New Year in at the Society smoker. He returned home quite suddenly, and this was the last occasion on which we enjoyed his genial presence, his humorous narratives, and his inspiring influence in paleontology.

HENRY FAIRFIELD OSBORN

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[1] "What Is a Species," *Amer. Nat.*, XLII, 184–94.

[2] "Has the American College Failed to Fulfil Its Function?" *Proc. Nat. Educ. Assn.* (1909), p. 526.

CHARLES RICHARD VAN HISE
1857–1918

My first impressions of Van Hise were received from the gifted and lamented Irving, when we were close colleagues on the Wisconsin Geological Survey, and when young Van Hise was a student of geology and related sciences under Irving at the University of Wisconsin. Only those who had the good fortune to taste the rare flavor of the brusque humor of Irving can appreciate how charmingly he brought out the traits of his promising pupil as he told of their good-humored laboratory bouts over problems in hand. These little tales of the laboratory come back to me now as precious reminiscences at once of the trainer and the trained; as also of the crude state of petrological technique with which they had to struggle. It was just at the time when the polarizing microscope was coming into use in America in the examination of thin slices of crystalline rocks, and when only a few of the better-trained and bolder young men were venturing to try the new art. Young Van Hise, working under Irving on the crystalline rocks of central Wisconsin, came to think that he had discovered a new characteristic of a certain constituent under study and became sanguine that it would prove distinctive and constitute a contribution of some notable value at that early stage of the new art. He was naturally elated and confident, but Irving, playing the part of the conservative and critical trainer, kept the young enthusiast's elation in curb by all sorts of objections, real and fanciful, and made light of the arguments he urged in support of his claims; but Van Hise held his ground sturdily and returned undauntedly to his lathe and his microscope to search out new evidences and to strengthen old ones until, in due time, he made good against all the probings and humorous pooh-poohings of his instructor.

This earliest picture of Van Hise's sturdiness of mind and invincible industry—reaffirmed as it has been so often in our long, intimate acquaintance since—has always seemed to me to portray

one of the most salient traits of his strong personality. He always seemed to realize that one must dig to discover, and that after he had brought forth his results and built them into a logical structure there would still be winds that would blow and storms that would beat and that, as a matter of course, the world would always be probing and pooh-poohing whatever he advanced, and so it was for him to lay the foundations so well and to brace the parts so firmly that the structure could meet the stress sure to be brought to bear upon it. Thus too he seemed quite willing to have his products go to the test and quite ready to accept the issue. This intellectual sturdiness and steadfastness, abetted by an instinctive adherence to purpose, stand out as conspicuous traits in the whole career of President Van Hise.

When he, in his turn, became an instructor, he repaid his debt to Irving by inspiring a gifted student of his own, young C. K. Leith, who in after years became his own close companion and co-worker. These three names, Roland Duer Irving, Charles Richard Van Hise, and Charles Kenneth Leith, will always stand together in the geology of the central crystalline area of our continent as a scientific triumvirate. Their great work is so intertwined that no one may completely separate it. Of this gifted trio Van Hise formed the middle bond.

The dominant qualities we have noted appear in quite another form; there was geographic persistence and centralization. It is a rather notable fact that from birth to death Van Hise's great activities, notwithstanding their breadth, clustered about his early home and centered in his native state. He was born at Fulton, Wisconsin, not thirty miles from his final resting place at Madison. His higher educational career began and ended at the University of his native state, to whose greatness he largely contributed. His scientific researches started with studies on the ancient rocks that form the nucleus of "Isle Wisconsin," and he seems ever to have come back to its symmetrical structure as a geologic standard. His public service, broad as humanity though it was, had its center and spring in the higher welfare of the people of Wisconsin and of the great commonwealth to which it belongs.

The academic career of Van Hise was a steady ascent; he passed upward easily and naturally from student in mechanical engineering, 1875–79, to instructor in metallurgy, 1879–83; thence to assistant professor, 1883–86; to professor, 1886–88; to professor of mineralogy, 1888–90; to professor of Archaean and applied geology, 1890–1903; and thence to the presidency of his Alma Mater in 1903, which he held until his death in 1918. He gave collateral academic service at the University of Chicago as non-resident professor of structural geology from 1890 to 1903.

His scientific career was a similar ascent from state and interstate relations to national and international relations. His early scientific work was connected with the State Geological Survey of Wisconsin and related to the crystalline formations of the central and northern part of the state, particularly the iron- and copper-bearing series. At the close of the State Survey these studies were transferred without interruption to the United States Survey and were steadily broadened to include other regions. He worked in close association with Irving until the latter's untimely death in 1890, when he succeeded to the direction of their common governmental work on the pre-Cambrian formations in the Lake Superior region and elsewhere.

The investigation of the crystalline rocks of the Basement Complex was the chief geologic task chosen by Dr. Van Hise. It is needless to say that it was pursued with characteristic ardor and enthusiasm until he was called to the presidency of the University of Wisconsin in 1903. The chief results of these geologic investigations appear in a series of large monographic volumes that stand as a monument of persistent industry and commanding ability. The more important of these are: *The Penokee Iron Bearing Rocks of Michigan and Wisconsin* (1892) [with Roland Duer Irving]; *The Marquette Iron Bearing District of Michigan* (1897) [with W. S. Bayley and H. L. Smyth]; *The Menomonee Iron Bearing District of Michigan; Geology of the Lake Superior Region* (1911) [with Charles Kenneth Leith]; *The Archean and the Algonkian* (1892); *Principles of North American Pre-Cambrian Geology* (1896) [Appendix by Leander Miller Hoskins]; "Some Principles Governing the Deposition of Ores," *Journal of Geology* (1900); *A Treatise on Metamorphism*

(1904). To these major treatises are to be added many contributions to scientific periodicals and to scientific societies, as well as addresses and minor papers of other types.

These monumental studies made Van Hise *facile princeps* in the great field of pre-Cambrian geology. His work is too broad and complex for analysis here, but it may be said to rise into two climaxes, the first structural in nature and best expressed in the generalizations of his *Principles of Pre-Cambrian Geology*, the other chemico-physical and best set forth in his *Treatise on Metamorphism*. No treatment of either of these almost illimitable themes could in his day, or in our day, or in the near future, be the last word on these intricate subjects, but the contributions of Van Hise must always be regarded as marking a great epoch in the progress of the geology of the earliest terranes.

It was one of the cherished ambitions of Dr. Van Hise to reduce the complex phenomena of early crystalline geology to the principles of chemistry and physics. His effort to do this appears in clearest terms in his *Treatise on Metamorphism*, but it also runs as a strong vein through most of his later geologic writings. His generalizations respecting metamorphic processes are perhaps to be regarded as his broadest studies and as his climacteric contribution to geological science.

In attempting now to summarize his work we must not fail to observe that just as some of the fruitful work of Irving came over by inevitable inheritance into Van Hise's work and enriched it, so some of Van Hise's work has passed over into the still evolving work of Leith and lives in it and will perhaps prove to have some of its best fruits in it as it gradually evolves. We must at least note that the fruitage of Van Hise's planting is still growing and ripening.

In the very nature of the case, work on the great iron- and copper-bearing formations of the Lake Superior region always gave a notable economic bearing to the studies of Dr. Van Hise, and so, as his mind always sought principles and generalizations as the most vital embodiment of specific facts, he was naturally led to draw important conclusions relative to the principles of ore deposition, particularly those connected with secondary

concentration. These are perhaps summarized best in his address as retiring president of the American Association for the Advancement of Science, delivered at Denver in 1901.

With his acceptance of the presidency of the University of Wisconsin, Dr. Van Hise made a serious and at first confident effort to continue his geological researches in addition to his administrative duties, but he soon became so deeply engrossed in the humanistic phases of his new work that there was little time left for effective research in the old lines, and so his foremost interest shifted to the new work. The two interests, however, merged, in a measure, in his study of the application of natural resources to the general welfare of man, especially the conservation of natural resources, to which he made several notable contributions, among them the best book on the subject.

It was natural to pass from this special line of economic study to the broader aspects of current commercial and industrial questions, where his chief interest seems soon to have centered on the organization and co-ordination of effort as the key to the solution of the vexed questions that agitate this field. Most notable among his writings in this line perhaps is his book *Concentration and Control, a Solution of the Trust Problem in the United States.*

The utter breakdown of the basis on which the leading industrial legislation of the United States had been based, as soon as the stress of the Great War forced the nation itself to become a vast industrial institution, and the precipitate resort of the nation to practices diametrically opposed to those embodied in its previous legislation, deeply interested President Van Hise and obviously rendered his previous views on co-operation and co-ordination still more definite and strong. At any rate, these views were urged with still more vigor in his last years and formed the keynote of his book *Conservation and Regulation in the United States during the War.*

President Van Hise was profoundly interested in the war and made its probable intellectual, ethical, and economic outcome a special subject of study. As an administrator he vigorously marshaled the resources of the institution over which he presided in support of a strenuous prosecution of the war, while personally he contributed directly to it by lectures, papers, and other service

of notable value. His most conspicuous service was the aid he rendered in the conservation and allocation of our food resources. As the war drew to a close he became especially interested in the formation of a League of Nations. He prepared an address on this subject in which, with his ever-present regard for the practical and the attainable, he drew with greater definiteness than most other advocates the features which such a league should, in his judgment, embody. This was essentially his last contribution to the public welfare.

As the administrator of a great educational institution he naturally regarded science as the bed rock on which educational practice should be based, but he did not interpret science in any narrow or technical sense; he viewed it broadly as an expression of the carefully sifted and thoroughly proved reality disclosed in each and every field of inquiry. Research as an indispensable condition for discovering, demonstrating, and enlarging the body of science, as also for rescrutinizing and renovating that which had previously passed for science, he held absolutely essential to a true university. He went farther and regarded it as essential also to education in all grades; for the renovation, the reconstruction, and the reshaping of the subject-matter taught in all the grades he held scarcely less vital to primary education and the public welfare than the addition of new subject-matter on the frontiers of knowledge. Important as he held original research to be, however, he held its application to the affairs of life and its incorporation into the lives of citizens as a working, guiding, inspiring factor to be an equally important function and an equally imperative obligation of a state institution. He was fortunate in coming into the presidency of an institution whose working lines were already set in the directions he approved. With this inherited advantage he pushed the university forward in its adopted lines with great success.

Respecting the debatable borderland between what is to be regarded as a permissible function of a state university, on the one hand, and what is to be regarded as non-permissible, or scarcely permissible—particularly in matters where organized bodies of citizens differ—on the other, President Van Hise was rather strongly

predisposed to magnify the former. He placed a distinctly broad interpretation on the functions of the university. He thought it not only the privilege but the duty of the university to give the state leadership even in lines regarded by some others as at least debatable. While this view did not go so far as to include the precise matters that divided the organized political parties, it yet did embrace matters closely akin to these, matters felt by some others to fall within the outer borders of party policy. The more conservative policy of leaving a clear margin of safety between the conceded fields of scientific inquiry in such matters, on the one hand—in which all right-minded citizens should concur—and the fields of party conflict, on the other, seemed to him to fall short of the full duty of the university to the state. As a natural result of his vigorous advocacy of some policies held by others as debatable, friction of the milder sort arose at times and made the path of his administration less smooth than it might have been under the more conservative policy, but this never went so far as to loosen the great hold of the institution or of its president on the affections and pride of the people of the state. His administration of the university was a declared success; both he and the university under his care exercised a profound influence on the intellectual and material progress of the state.

From May 29, 1857, to November 19, 1918, was the span of a remarkably fruitful career. It was, we grieve to note, two decades short of the full period of fruitfulness we had ground to hope for, but the vigor and intensity of the work, its solid nature, and its effective usefulness made good, in some large degree at least, the shortage in time. President Van Hise's contribution to the world has been very large and very rich.

His home life was singularly happy, though shadowed in his last years by the death of a beloved daughter. He leaves a devoted wife and two affectionate daughters. His personal qualities were of the highest order. He was a congenial companion in the office, the laboratory, and the field. His point of view was large and liberal, always incisive, often humorous. His convictions were strong, and the courage of his convictions never seemed to fail him.
was outspoken and manly in bearing, frank and strong in his

friendships. He respected the sincere, and called forth sincere respect in return.

He received a due measure of the honors his work merited. Williams, Dartmouth, Chicago, Yale, and Harvard conferred upon him their highest honorary degree. A long list of scientific societies in this country and abroad honored themselves and him with membership. He was chosen to the presidency of practically all the scientific societies to which he could be regarded as naturally eligible.

THOMAS CHROWDER CHAMBERLIN

HENRY SHALER WILLIAMS

1847–1918

Professor Henry Shaler Williams died in Havana, Cuba, on July 31, 1918, at the age of seventy-one years. During his lifetime he had been one of the leaders in his profession and was a pioneer in the modern practice of studying fossil faunas as units for investigation, as contrasted with the practice of collecting and describing fossil species.

Professor Williams spent his college days at Yale, where he graduated in 1868. His interest in natural science led him to continue his studies as a graduate student, a rather unusual practice in those days, and he was granted the Ph.D. degree in 1871. The following year he held the position of professor of natural history in the University of Kentucky, after which time a break occurred in his scientific career. For eight years he was engaged in business with his father and brothers, in Ithaca, New York, but during this whole period his real interest was in natural science, and he never gave up the idea of devoting his life to the pursuit of science.

Although his early scientific work in Yale had been in zoölogy, and he had made some contributions to the literature of that subject before 1872, when he returned to scientific work in 1880 he entered the faculty of geology in Cornell University. His earlier zoölogical interests naturally directed his geological work toward the field of paleontology, and he entered his new field of activity with the point of view of a man of science rather than as a professional geologist. His lack of close association with scientific work during the period immediately preceding his connection with the Cornell faculty led him to enter his new work with an independent attitude of mind, which is perhaps responsible, in part at least, for his early pioneer work. He at once set about the search for problems to solve, and he found them in plenty right at home. His own experience during those early days at Cornell led him to advise his students always to search for and solve the problems that were

to be found in their own dooryards rather than to think that any problem worth solution must be sought for in distant parts of the earth. His exceedingly careful investigation of the geological section at Ithaca, with the careful collection of fossils from bed to bed and the study of their associations in faunas and faunules, and his observations upon the geologic range of species and their recurrence at different horizons in the section really brought to the attention of students of fossils a new field for research and new problems whose relations to the problems of the stratigraphic geologist were much more intimate than the mere search for and naming of new fossil species.

For a number of years he continued his studies of the fossil faunas of the Devonian in central New York, making careful comparisons between the faunal succession as he had found it at Ithaca and the succession in other sections farther west, which represented the same time interval. The results of these very careful observations upon the faunas and their stratigraphic relations led to his proposal of the doctrine of "shifting faunas" within the limits of a single basin, the movements of the various faunal associations being governed by changing environmental conditions. All these studies led him more and more to the consideration in its broader aspects of the succession of life forms upon the earth, and directed his studies into the field of organic evolution as exemplified by the actual geological history of organisms.

The unique character of Professor Williams' investigations of the Devonian faunas of central New York early called attention to his studies and led to his selection as director of the Devonian work of the United States Geological Survey, to which was also added the direction of the work upon the Carboniferous. His survey connection made it possible for him to extend his studies into broader fields but did not lead to the severing of his university ties. Among other problems his survey work led him to the study of the Devonian faunas of Maine, and his latest contributions to the literature of paleontology have had to do with the Devonian and Silurian fossils of that state.

In 1892 Professor Williams left Cornell University to become Sillman professor of geology in Yale University, where he succeeded

Professor James D. Dana. He remained in this position for twelve years, when he returned to Cornell and continued his work there until his retirement as emeritus professor of geology in 1912.

Professor Williams' name will always be associated with the development of American paleontology and more especially with the American Devonian. His more philosophical contributions, however, are applicable to the life of all periods.

As a teacher Professor Williams exercised a great influence in the encouragement of his students in research. He did not believe in directing each separate step which his pupils took, but he believed rather in leading them to search for their own problems and when found to solve them independently if possible. He considered the field of scientific paleontology to be limited in its possibilities for a livelihood, and consequently he never offered undue encouragement to prospective students to enter the work. To those who were bound to enter, however, he gave the best council and advice of which he was capable. He was especially a laboratory teacher, and he made his students feel that they were companions with him in research. He was a man of most amiable disposition and spirit, and his kindly smile could never fail to reach one's heart. He was a loyal friend and always rejoiced in the success of those who had come under his instruction.

Stuart Weller

WORLD-ORGANIZATION AFTER THE WORLD-WAR—AN OMNINATIONAL CONFEDERATION

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It seems quite needless to say that the world-war now in its closing stages forms a crucial epoch in world-history, that its origin was closely linked with events running far back into the past, or that the outcome will vitally condition the future. It seems no less needless to say that the whole history of the earth, in its broadest sense and in its utmost reaches, has been closely linked as a co-ordinated series of events and will remain so linked far into the future; or that the material factors in this world-history are intimately intertwined with those that condition life as well as mental and moral issues. And so all episodes in world-events, however special they may seem on the surface, are to be viewed as factors of a co-ordinated unit in which each event plays its part in the composite whole.

And yet with little doubt every reader, at first flush of thought, will feel a touch of surprise that a discussion of world-organization after a world-war is given a place in a magazine devoted to earth-science, however broadly that periodical may try to cultivate its field. But in the face of this, and with due deliberation, a medium has been chosen in which discussions of former crucial stages of earth-history are wont to appear and a scientific atmosphere habitually invoked to control the spirit, the purpose, and the method of discussion.

The European balance of power and the European concert as peace devices.—Before the war, the control of international affairs in Europe was sought by means of a "balance of power," with a Triple Alliance in one pan of the scales and the Entente Powers in the other. The periodic disturbances of this balance and the recurring threats of discord in the "concert of powers" left the way open for sinister underplays; a series of wars arose in spite

of the efforts to keep the peace, and these wars led up to the recent gigantic conflict. So this equilibrium scheme for the preservation of peace must take its place among the list of futile efforts. The way in which the balance was disturbed reveals the point of danger in all such schemes. Almost at the opening of the war the Triple Alliance fell apart and was soon replaced by the "four-in-a-row" combination so significantly strung on the Berlin-Bagdad line, while the Entente group became a center of accessions and gradually grew into the "associated nations" that have just triumphed in the military stage of the struggle. As the inevitable result of such radical shifts of alliance, confidence in the reliability of alliances as a guaranty of peace is greatly weakened. The thoughtful world is therefore casting about to find some other form of organization that gives promise of controlling world-affairs more successfully.

The proposed League of Nations.—In lieu of a balance between alliances, a single league of nations, so strong and so inclusive as to dominate the world, is the favorite scheme of the hour. The factors that are to unite to form this proposed league are still, as before, the several nations, and these nations are to carry into the compact, as before, all their diversities of nature and interest. These diversities give reason to question the endurance of the new league when new lines of stress shall arise. All past leagues have given way in time; why should not this? But what other course is possible? What but the nations as they happen to be can enter into compact to preserve the peace? Can the diversities be set aside and the nations unite on a common homogeneous basis? This is the soul of the proposal here submitted.

The elements of a homogeneous basis.—It seems altogether practicable to divide the interests of the nations into two quite different classes, the first to embrace inherent rights shared alike by all, such as appropriate conditions of self-determination, of self-development, of intercourse with the rest of the world; the second class to embrace such more special interests as spring from the individual natures, inheritances, or peculiar preferences of each nation, those for example that grow out of the affinities of race, language, religion, modes of life, social ideals, and trade preferences. The first class

of interests are necessary to the normal existence and development of a nation, and by reason of this are stable and essentially irreversible; the second, to a notable extent, are merely preferential and naturally are subject to change and even to reversal with alteration of conditions.

Because of these radical differences there is reason to believe that all right-minded nations can be brought to support with constancy and fidelity such measures as may be found necessary to establish and to maintain a common control of the first class of interests, because these are as indispensable to their own welfare as to the common welfare, while they might take diverse attitudes in relation to measures intended to promote some aspects of the interests of the second class. Even if they united on these under given conditions, they might separate with change of conditions.

A further separation of the fit from the unfit interests is necessary for a practical working scheme. Only those interests that are tangible, measurable in physical units, and registrable in definite terms are well suited to successful administration.

Just how these essential qualities may be combined in a working scheme will appear a little later. Just here let us hasten to note that there is no antagonism or incompatability between a new omninational organization based on common interests and inherent rights and a new league of nations based on special national interests; on the contrary, the placing of common interests and inherent rights under an omninational body created for the purpose leaves the remaining interests for national alliances based on the affinities and preferences of the nations concerned. The adoption of an omninational scheme contemplates supplementary leagues of a more special sort as its inevitable complement.

The peculiar fitness of the existing league of nations for the settlement of the war issues.—The war issues are now in the hands of a league born of the stress of war conditions. As the product of these special stress conditions, it fits the requirements of the war settlement to a supreme degree; it was born to meet them. This war-born league has already won in the military contest; it is more likely than any other possible league to meet the requirements in

statesmanship that are now imminent. Without essential addition or modification, the "associated nations" constitute a league supremely fitted to bring to a close the present issue, to guide in reorganization, and to hand the conduct of world-affairs over to new organizations born of the new peace conditions and fitted by such birth to insure a great era of peace in the future. In its military and material power, in its collective intellectual prowess, in its indomitable purpose, and in its moral fitness, this war-born association of nations cannot be greatly strengthened by any accessions now available, while it might be much hampered by such accessions. It could scarcely be strengthened by the addition of peoples who have been idle bystanders or equivocal onlookers during the great conflict. It could scarcely be strengthened by the addition of the little neutral powers, so unfortunately located on the borders of the aggressive empires that they have been forced, willingly or unwillingly, to be the avenues of supply for the aggressive forces. It could gain little power or fitness for its function by additions from the Russian empire, once a co-ally, whose dissolution has given rise to half-formed republics on the one side, and on the other to an autocratic oligarchy more deplorable than the autocracy from which it sprang. The war-born league of associated nations, in the form in which the stress of war brought it into being, is itself the most fitting league to guide and control the great interests of mankind until it shall have achieved the more complete triumph that remains to be won through a wise settlement. For the immediate future, therefore, it is in the highest interests of mankind that events should take shape under the leadings of the league that has brought us to this first stage of triumph.

The punitive war function versus the requisite impartial peace function.—Supremely fitted as the war-born league is for the settlement of the immediate issues of the war, it is not altogether well suited to be the immediate instrument in building up a spirit of peace. The war issue cannot be settled either in justice or in wisdom without due punishment for the unlawful deeds of the war. The security of the future demands that the guilty be adequately punished. The war-born league cannot therefore divest itself of the memories of the war or of the punitive measures that must

follow. The animosities engendered in the war and in its settlement are likely to linger for three or four generations at least. The "associated nations" must continue to stand sponsor for the complete fulfilment of the reparations it decrees and it cannot escape, and ought not to wish to escape, the associations that cling about the dispenser of justice.

On the other hand, the body that is to develop a permeating and profound disposition toward peace should be as impartial as an inorganic law. It is one of the special features of the proposal herein offered to create a body whose actions shall be as nearly impartial as possible by resting them on a foundation of which parity is the cornerstone. The punitive function of the war-born league stands in contrast with the impartial function needed in the new organization which is to develop a lasting spirit of peace. It is therefore believed to be best that the punitive function be carried into effect by the "associated nations," while the impartial functions looking toward lasting peace be committed to a newly formed body whose constitution shall equally fit it for its special function. It is quite obvious that the punitive action should be taken as promptly as practicable and be carried steadily and firmly into effect until its terms are fully satisfied, or at least fully assured of satisfaction. It seems almost as obvious that this punitive work should be done and out of the way, so far as practicable, before the impartial régime for the development of the peace spirit shall be instituted. This does not mean that all penalties should be actually satisfied in full, but merely that they should be adjudicated and the satisfaction guaranteed. These vital considerations seem to point out, not only the nature of the bodies best fitted for these two functions, but also the order of their actions.

The settlement of the immediate war issues a necessary step toward new organization.—There should be no illusion respecting the present status of the great issue. The triumph of higher ideals has indeed been begun and begun auspiciously, but it is far from complete. The military victory is great, but victories in statesmanship no less great are necessary to make the ultimate issue really triumphant. Certain steps toward settlement obviously need to be taken at

once; others, if wisely taken, must necessarily be delayed. Time is imperatively demanded for the processes of reorganization. Four dynastic empires have fallen into chaos. At their best they were little more than forced agglomerations; they were not true nations. They were formed of diverse and discordant materials bound together by dynastic force, not by spontaneous coherence. Some of the people thus agglomerated were held in hated relations by a duress little short of slavery, though they were worthy of an honored place among nations. The gallant Czecho-Slovaks have shown their worthiness in a heroic, not to say dramatic, way. The crumbling of these agglomerates leaves a chaos of distraught peoples, some of whom are worthy material for reorganization, others of whom are but the morbid products of unwholesome conditions. These morbid products are the greatest threat of the crisis as it stands today, a greater threat, indeed, in some respects than the dynasties from which they have sprung. Like an eruptive fever, this sinister offspring of autocracy has broken out on the surface and shown its full malignity, the better to point the need of treatment. The disease is likely to run its course, but the danger of contagion calls for firm and wise treatment. The war-born alliance of nations is the appointed power to deal with this diseased state and to rescue the wholesome factors of the defunct empires from its deadly ravages. The call to this function is imperative and immediate.

A period of national reconstruction necessary.—When this deadly fever shall have burned out the morbid inheritance from the defunct empires, the worthy elements that remain will need time and aid in segregating themselves according to the natural laws of national evolution, as also in assuming the conditions of normal national life and in entering upon the functions of true nationality, before they can wisely become parties to the final settlement. The task of the associated nations in this process of national reconstruction is likely to lie in at least four lines—the preservation of order, the establishment of stable governments, the arbitration of contests respecting boundaries, and at least preliminary provision for outlets and inlets. The last two functions raise issues that must run on into the far future and should be influential factors in giving shape

to the organization later to be instituted in the interests of permanent peace.

This indispensable interval for segregation and reorganization into new nationalities may perhaps be placed at three to five years; the delay may be a sore trial to the impatient, but it seems imperative to safe procedure.

A further test of the principle of allocation of resources.—During this period of reorganization, and in the performance of the obligations which have been thrown upon the associated nations by their triumph, they will almost inevitably carry forward the present experiment in the control and apportionment of the resources of the several nations that make up the league. This allocation of resources is, in the minds of some of the most thoughtful students of the issue, regarded as the central working idea of the proposed league of nations. It is apparently not so in the minds of others. The control and apportionment of resources has been a most vital feature in the workings of the association of nations while it has been winning the war. The pressing needs of the impoverished and starving peoples of Europe will make a continuation of this allocation indispensable for some time to come. During the stress of the war, the conditions under which the control and distribution of food and other resources have been tried were quite exceptional, and it is by no means clear to what extent even the most right-minded peoples will be willing to submit to the deprivations that have attended this system, when the stress of war and the call to sacrifice are gone. But as the war conditions pass away and peace conditions return, the application of the system may be tested in a more nearly normal way. The allocation of resources is no part of the scheme herein proposed but may be a consideration in forming supplementary leagues. It is applicable to that class of international interests that we have put in the second class because they relate to the *diversities* of national interest rather than the common interests on which the proposed omninational organization is to be based.

The new nationalities to be considered.—One of the first steps looking toward lasting peace is the development of normal nationalities out of the autocratic agglomerates. The factors that

constitute normal nationality are not only complex but they vary in value in different cases. As a result no *simple* definition is possible, nor will any *single* definition suffice. Each nationality carries its own special combination of characteristics, which vary with the value of the several factors that enter into it. And yet in each concrete case presented it is usually possible to form a fairly just opinion of what peoples should form separate nations. But even then the border lines between such nations are often extremely difficult to fix, because there is more or less of mixture of diverse peoples and patchy inter-distribution. The only practicable mode of procedure seems to lie in fixing the bounds as well as may be and letting time bring about a better accommodation.

It is fairly clear that the Polish people, the Czecho-Slovaks, the Jugo-Slavs, the Anatolians, the Armenians, the Syrians, the Palestinians, the Arabians, and the Mesopotamians should be seriously considered as candidates for organization into independent nationalities, but their claims vary much, both in kind and degree. So, also, it seems clear that the provinces wrested from France by force should be returned to her, that the provinces taken from Italy should be returned to her, that the Rumanians should form a single nation, and that various rectifications of bounds are needed in the Near East, while some rectifications of border lines of Belgium, Holland, and Denmark are desirable, if they can be agreed upon. The grave question whether a single new nation or a group of related nations shall emerge from the chaos of the great empire of Russia is as yet too much beclouded by uncertain conditions to warrant discussion, but it obviously constitutes an imminent problem of the future.

The problems presented by these candidates for recognition as independent nations are already taking shape and will find preliminary settlement in connection with the other war issues, and so the specific proposals of this paper are offered on the assumption that most of these peoples will have organized themselves into true nationalities and will have been recognized as such by the associated nations before the proposed general confederation shall be formed. The lines on the accompanying map are drawn on the assumption that the peoples named will form independent nations. If these

lines are not those which shall ultimately be established, the principles they are intended to represent will still remain applicable to whatever lines shall obtain.

THE BASIS OF THE NEW ORGANIZATION

World affairs center about international intercourse. The exchange of products is its most tangible phase. Some of these products are material, others mental or moral, but only the material products are measurable in definite terms, and so these only are well suited to be the basis of a concrete working scheme. As a rule mental and moral factors run apace with the material, but this is not always closely and accurately so. And yet the material exchanges form a fairly just representation of the whole intercourse. Commercial exchange is therefore made the basis of the scheme of omninational conduct of world-affairs herewith offered. It has two obvious factors: (1) provision for intercourse, and (2) equitable administration of such provision in the interests of all peoples. The ethical ideas at the bottom of the proposals may be expressed concretely as follows:

A. *Fair opportunities for commercial and other intercourse between all peoples under such reasonable economic regulations as they themselves may impose.*

B. *Protection and regulation of international intercourse by an omninational body representative of all peoples in proportion to their participation in international commerce.*

Our nation is openly committed to the endeavor to secure for the peoples in the heart of Europe outlets such as will permit them to reach the high seas and take their rightful part in the commerce of the world. The right of the rest of the world to access to these peoples is only the other side of the equation. Some such provision is regarded as indispensable to lasting good will, and hence to stable peace as well as the common prosperity.

Three types of common commercial highways—world-ways.— 1. The high seas are already recognized as the common highway of all peoples. Respecting them, it only remains to insure their equitable control in the common interest of all peoples. It is proposed to secure this by means of an omninational organization, an

Omninational Confederation, if you please, in which all peoples who engage in international exchange in any appreciable way shall be represented in proportion to their participation. Some details of the mode of organization will be discussed later.

2. While the high seas are thus recognized as common commercial highways, there are certain straits and lesser waterways of other types that are not now equally open to unrestricted commerce. It is proposed that all these shall be opened to general commerce and that they shall be placed in the care of this Omninational Confederation, whose duty it shall be to see that this freedom of use by all the nations is maintained. The freedom of these straits is not, however, to displace those proper restrictions relative to coastal and internal waters that, by common consent, are regarded as essential to national safety and the interests of domestic commerce.

3. A very special problem is the provision of outlets and inlets for peoples occupying lands in the heart of Europe and elsewhere completely surrounded by the lands of other peoples. Commercial highways for these peoples can therefore only be *thoroughfares on land.* In solution of this critical problem, it is proposed that there shall be provided under the authority of the proposed Confederation omninational rights of way on the land, on which shall be located railways, roadways, and other thoroughfares, so placed and so maintained as to constitute world-ways for intercourse between these peoples and the rest of the world.

Pre-eminent domain.—As a basis for establishing and administering these common highways, it is proposed that the Omninational Confederation shall assume the right of pre-eminent domain on the ground of common welfare in precisely the same way that states, provinces, municipalities, and even townships now exercise the right of eminent domain.

These world-ways as barriers against aggression.—The proposed world-owned land-lanes are to be so chosen as to constitute also *barriers against aggression.* As the property of the world at large, taken over for the common welfare under the principle of pre-eminent domain and placed in charge of the Omninational Confederation, it will be within the province of this representative body

to interpose objections to the violation of these highways by one people in attacking another people or by one group of peoples in attacking other peoples, if such attacks contravene the general welfare. It shall be within its power to enforce its protest, if necessary, by an Omninational Guard maintained for the purpose of protecting and policing the omninational property. The very policing of these highways will in itself be a means of preserving the peace.

The relations of the world-ways to national boundaries.—To serve as such barriers to aggression and at the same time to serve equally the peoples adjoining these highways on either side, they are to be placed on or near international boundaries so far as topographic and other natural conditions permit, but they are not themselves to be the boundaries, which will be fixed independently. The world-ways may therefore depart from them more or less freely as conditions require. While broadly serving the commercial interests of the world in general, they will be specially tributary to the interests of the adjoining peoples, as are all highways. The project, should, therefore, if fairly understood, be very kindly received by the peoples of the lands traversed, and the benefits arising from these highways should promote good will toward their establishment, as also toward their maintenance in times of stress.

The proposed gridiron of omninational highways.—In the area most involved in the world-war, it is proposed to establish four north-south omninational highways stretching from appropriate terminals on open-water bodies at the south to similar terminals at the north. Crossing these from east to west four highways of like type are proposed, the whole forming a gridiron of omninational thoroughfares. These are so placed and so related to one another as to give essentially all the peoples of Central Europe outlets and inlets for universal commercial intercourse, as may be seen from the accompanying map. The principle back of this gridiron of commercial highways is precisely that which underlies the public highways of enlightened lands. Put continents in the place of counties, put nations in the place of farmers and lot-holders, and the proposed world-ways serve much the same function as our streets and public roads. What our forefathers put in the place of

Indian trails, we propose in analogy to superpose on the dynasty-ridden domains of Central Europe and Asia Minor. Some of the leading details will be discussed later.

The highway problem of Asia Minor.—The Asiatic area of conflict presents some special difficulties and may therefore be treated on a special basis. The Black Sea on the north, the Bosphorus, the Sea of Marmora, the Dardanelles, and the Aegean Sea on the west, and the Mediterranean on the south, mark off Anatolia in a definite natural way as the appropriate home of the Ottoman peoples. Nowhere else are these peoples the preponderant nationality. Even here their dominance is qualified by the presence of numerous Greeks, Armenians, and the modified descendants of many ancient peoples. To complete the delimitation of Anatolia according to the method of this scheme, it merely remains to open an omninational highway from the northeastern apex of the Mediterranean over the plateau to the Black Sea, separating Armenia from Anatolia in response to the call of outraged justice. Neither sharp racial limits nor convenient topography lends itself very happily to this demarcation. No doubt lack of a marked natural boundary has contributed largely to the racial intermixture that prevails, but without question the massacres of five centuries are the chief reason why the Armenians are not more preponderant than they now are in their home region on the culminating plateau that has its apex at Mount Ararat.

There is sore need for an open highway across the heart of Anatolia, not only for the sake of its own people, but for that of the lands beyond, which have suffered grievously in the past from isolation and oppression. It is proposed therefore that the Omninational Confederation shall take over and administer the Constantinople-Bagdad railway and develop its connectons so as to make these serve as a gridiron of thoroughfares to and from the rich fluvial plains, as well as the oases of the arid tracts of the Near Orient. Under proper supervision, six productive, prosperous peoples should arise where poverty, degeneracy, and suffering have prevailed for five centuries. All these six lands—Anatolia, Armenia, Mesopotamia, Syria, Palestine, and Arabia—are sufficiently distinct in physical features, races, languages, traditions, social and religious institutions, to entitle them to be treated as independent

MAP OF PROPOSED OMNINATIONAL HIGHWAYS (IN COLOR)

peoples, though they will need help, guidance, and guardianship while they are developing themselves. All have been great in the past and all may be again. It will be a blessing even to the Ottoman people to be relieved of their debasing dynasty and the burden of the name that has fastened itself upon them—"the unspeakable Turk." Relocated in their old home in Anatolia and developed anew on modern lines as Anatolians, they should in time take a worthy place in the progressive world, for the Ottoman people, fairly judged apart from their dynasty, are not without their merits and possibilities.

Relations of omninational highways to other transportation lines.—The main dependence for rendering these highways effective is placed on railways either taken over or built anew by the Confederation. It is assumed that they will have a construction, equipment, and administration worthy of the high purpose they are to serve and of the world-body that establishes and administers them. It is further proposed that, so far as may be wise and practicable, these highways shall be supplemented by waterways on rivers, lakes, and canals, and by common roadways adapted to motor travel, so that the whole shall be as effective and adaptable a combination as may be. Furthermore, it is proposed that these omninational lines shall work in as close co-operation as practicable with the national and corporate lines of the same regions, helping to bind the whole into a mutually helpful system of transportation. An important practical distinction between omninational and other lines will be discussed later.

The bearing of the proposed measures on the thirst for national possessions.—The thirst of overlords and feudal castes for greater and greater possessions is easily understood, but fair-minded people of the benevolent order see little reason to desire the irksome task, the great expense, not to say the critical risks, incurred in subjugating and governing weaker peoples, *provided* fair opportunities for economic intercourse with them can be secured *without such grave burdens.* Under the inherited habit of exploiting subject peoples, possession has naturally been regarded as a prerequisite to economic advantage, and so the cost and danger of acquiring and administering national possessions has been accepted as the price of such advantage. But if open doors and fair opportunities can be

maintained by common action, what remains to justify these costs and risks, not to add the inevitable fear of revolt, the constant preparedness to suppress it and to defend possession against rivals, together with the debasing moral atmosphere that surrounds the relation of master and subject? The proposed opening of all doors by a representative omninational body should lead to a lingering death of the inherited thirst to possess and to rule the lands of other peoples. If this be thought more ideal than real, let the spirit that has guided the people of the United States in their rise to power and prosperity, *as actually expressed again and again in action and in attitude*, bear witness.

The province assigned the Omninational Confederation.—The dream of a single world-nation with a single world-government without doubt is highly laudable and will perhaps in time be realized, but in the cold light of existing facts the full realization of this great dream hangs on the attainment of a state of human evolution only likely to be reached by the world at large in the distant future. Many peoples are yet in the infantile stages of their development and are still far from a state of fitness for full participation in world-management. Grading up from these children of our race, there are peoples in various stages of adolescence and corresponding limitations of fitness, while even those that esteem themselves more advanced have, as this war testifies, only doubtfully entered on a state of intellectual and moral maturity.

Two things therefore seem obvious: (1) that a world-organization based on the hypothesis of national equality and governmental competency would be premature, and (2) that a governmental attempt which should try to compass all the intangible ideals that enter into the social desires and the political aspirations of the many diverse peoples of the world would prove impracticable at the present time.

On the other hand, it seems equally clear that certain great steps in advance are practicable and are therefore imperative. The groundwork for such steps seems manifest on due consideration.

1. *The commerce of the world is a concrete, measurable activity.*

2. *It offers a workable basis of control and administration.*

3. Inasmuch as each nation's commerce is definite and registrable, *a graded participation in control and in administration is entirely practicable.*

4. *Such control and administration is in its nature both just and conducive to the common advantage.*

In the light of these two groups of contrasted deductions, it is now to be said, with emphasis on the distinction, that the Omninational Confederation is *not* proposed *as a mode of political or social government but as a co-operative economic agency* controlling the essence of international affairs. It involves, to be sure, such commercial regulation and such control as is necessary to realize the purpose sought, but there its governmental function ends. It is assumed that so long as races and peoples remain as diverse as they now are it is best that each distinct nationality shall give shape to its own political and social devices and shall control its own local institutions as suits itself best. The proposed omninational effort is limited to concrete affairs of wide international concern, *affairs in which co-operation is indispensable.* The proposal is in the line of divorcing what is essentially racial, political, social, and provincial from what is economic and general. Interchange of products is always necessary for mutual comfort; not seldom necessary to escape starvation, as we now realize as never before, and as we are likely to realize more fully still as the need for food nears the limit of food production.

It is believed that a movement which draws a practical distinction between *political government*, on the one hand, and *co-operative economic regulation*, on the other, will gradually remove the inherited motive for aggressive rulership. Such removal should open the way for a freer adaptation of the special forms of government to the preferences of the peoples concerned; it should tend to abate the thirst for empire.

The functions assigned the Omninational Confederation.—It is proposed that the Omninational Confederation—

(1) Shall take entire control of the policing of the high seas and of such regulation of international commerce upon them as may be necessary and equitable;

(2) Shall take control, in the same sense, of such straits, channels, and lesser waterways as are essential to free international commerce;

(3) Shall exercise the right of pre-eminent domain on the land so far as required in providing avenues of intercourse between distinct nationalities, and shall have power to establish, maintain, and operate such thoroughfares; and

(4) Shall have all the powers requisite to carry into effect the purposes herein set forth.

The ruling bodies of the Omninational Confederation.—To be effective, the Omninational Confederation must be fully organized in a way appropriate to the specific work assigned it. This is likely to be more nearly analogous to corporate business than to the multitudinous legislation of ordinary political governments, and so the function of the ruling bodies may perhaps better be shaped after the most approved patterns of great corporations than after those of political bodies, but of course different forms of organization are consistent with the general scheme, and the plan herewith outlined is merely tentative.

It is important however here to note that the basis of the scheme, international commerce, makes it possible to give each nation that enters the Confederation *a voting power in strict proportion to the part it takes in international commerce.* This gives not only an ethical basis for the conduct of the affairs of the Confederation, but great adaptability to the practical working of the plan as in the case of business corporations. Since nations are negligible that take no part in international commerce, either as carriers or shippers of commodities, all recognizable nations may participate proportionately in the Confederation, and it thus satisfies the title Omninational.

The two factors that make up international commerce, (1) transportation and (2) commodities transported (exports and imports), are sufficiently different to constitute a working basis for two types of representatives, as also two sections of the ruling bodies, and so secure the well-known advantages of a bicameral organization.

It is proposed that the several nations be represented by delegates, who shall form a Congress the function of which shall be to determine the general regulations that shall govern the conduct of

the affairs of the Confederation and to choose directors and certain other officers who shall be more immediately charged with the business of the Confederation. The directors are to be chosen on the proportionate basis and their voting powers in the decisions of the directorate are to rest on this basis. Further suggestions respecting the ruling bodies and the judiciary will be made after the remaining features of the scheme are sketched.

The permanent seat of the Confederation.—It is proposed that the permanent seat of the Omninational Confederation shall be Constantinople, for these reasons:

1. Constantinople has long formed the center of those chronic difficulties that have called for some such remedy as is herein proposed. For nearly five centuries almost continuous trouble has centered about or radiated from Constantinople. The body that is to bring peace out of this prolonged agony may well sit at the seat of trouble.

2. The permanent occupation of Constantinople by a body representing the commercial interests of the whole world would of itself settle one of the most serious problems of the Near East, the possession of this strategic situation; possession by all nations jointly, not by any one alone.

3. The nationalities that most need to be led into the newer and broader national spirit would be nearest the new seat of influence.

4. Placed near the meeting-point of the three grand divisions of the Eastern Hemisphere, the Confederation would be seated where its later work, the economic development of these grand divisions, especially Asia and Africa, would be close at hand.

The naval and military forces of the Confederation.—Two vital considerations are to be met in providing the Confederation with an efficient navy to protect and police the seas and enforce its decrees, if that shall be necessary: (1) There should be no increase in naval or military armament; (2) there should be no weakening of the control of the right-minded nations so long as danger from the inherited spirit of aggression lasts. At the same time, it is agreed by the right-minded nations that a reduction of armament is extremely desirable if not imperative, because of the great financial burdens already incurred in the war. How can these requirements be met?

1. It is proposed that the Confederation shall take over war-vessels from the present navy of each of the nations, by definite units, such as a war-vessel with its officers, crew, marines, and full equipment, in such number as shall represent its equitable proportion of the navy of the Confederation. Let this proportion on the average be *one-third* of the existing navy, leaving on the average two-thirds remaining in the hands of each nation. Let one-half of this two-thirds be retained as the domestic navy of each nation, and let the other half be retired by such nation and be dismantled by it, so far at least that it shall not be an immediate menace to any other nation but still could be restored to service, if emergency required, in less time than any other nation could build vessels anew. Let all building of new battleships, and other vessels for which there is no need except in case of war, be discontinued by all nations.

Now under this plan (1) the *ratio* of naval power between the several nations remains practically the same as it is now; (2) the relative preparedness for war is the same; (3) the chief need of war-vessels is removed by the fact that the policing of the seas is taken over by the Confederation; (4) its system of parity removes the costly race to keep each national navy ahead of rival navies; (5) one-third of the existing expense of maintenance is saved to each nation; and (6) the burden of maintaining the Confederation's navy could probably be met by levies on the commerce protected by it, but if not it would be distributed on an equitable basis. The saving would thus be large, there would be little change in the relative power or preparedness of the nations, and any minor change that might be involved would be merely such as is likely to arise inevitably from the growth of commercial activity. It would be the height of prudence for all nations liable to suffer a change of relative naval power from relative declines in international commerce to forestall the adverse conditions of the future by entering into an equated world-scheme before their advantages pass away. It is important to note that by this plan of division of existing navies the nations that now have strong navies and are active in international commerce take no serious risks in trying the omninational scheme; for, let it be emphasized, the Omninational Navy

is to be made up of national units in equitable proportion, so that should the Confederation go to pieces the pieces would naturally fall back into the several national navies and their relative strength would be much the same as before and as they now are. The scheme does not destroy or trammel national preponderance but merely adjusts it to the rest of the world and the rest of world to it on a basis of ethical parity.

All existing submarines should be scrapped and heavy penalties visited upon every surreptitious effort to make any new ones. Submarines promise little or no constructive service to mankind; they are inherently dangerous to the common welfare. There can be no use or excuse for them, except on the presumption of war; and it is that presumption that we are trying to remove.

Land forces adequate to protect and police the borders of the straits, the terminal ports, and the omninational highways are to be taken over, in military units, from the several nations on the proportionate basis. The effect of this on the existing balance of power will be of much the same order as that of the sea forces, but the details are less readily stated and perhaps less important.

The manufacture of arms and munitions.—As a supplementary precaution against war and especially as a source of safety in peace, it is proposed that the several nations for themselves respectively, and the Omninational Confederation for itself, shall take over *a complete monopoly of the manufacture of arms and explosives of all kinds*, and that no person shall be allowed to make, possess, carry, or use arms or explosives of any kind except under regulations and provisions instituted and maintained by the several nations respectively for their own territories and by the Confederation on the seas and world-ways, the purpose being to suppress the harmful use of arms and explosives now so widely and destructively prevalent. Ample provision would of course be made for the sale of explosives by the respective governments for use in mining and for all other legitimate purposes, as also for the use of arms for the destruction of obnoxious, harmful, and dangerous animals and in legitimate sports.

This universal monopoly of munitions would greatly aid in the suppression of brigandage in ill-governed lands and of riots everywhere, as well as assist in the ordinary policing of all countries. A

rigorous system of accounting and inspection of the national factories of munitions would aid in maintaining an equitable apportionment of these to industrial needs and to the domestic armies and navies agreed upon between the Omninational Confederation and the several nations.

The financing of the Confederation.—The moral basis for financing the Confederation lies in the great saving of expense and man-service that will be secured by the common policing of the highways of international commerce on sea and on land. It is obvious that when such a system is once organized and has secured the confidence of all right-minded nations, the proportionate expense of insuring peace throughout the world will be reduced to a mere fraction of what is now expended in the maintenance of the several great armies and navies of the world. Since each nation will thus be relieved of an enormous burden of expense and loss of service, it will be but a matter of just reciprocity and of honor to meet its part of the expense of the common body that has brought the relief.

But after the system is once established, even this contribution may not be necessary. It is proposed that the revenues from the commerce benefited shall pay the cost of the benefits it receives, as nearly as may be, by appropriate charges for shipping facilities, traffic rates on the railways, and various fees fixed with a view to meeting the costs, upkeep, and administration involved.

The credit of the Confederation, resting upon the credit of the constituent nations, should be an ample basis for such loans as may be required to inaugurate new enterprises. At the outset, however, the specific financial aid of the constituent nations may be required.

DETAILS AND SUPPLEMENTARY DISCUSSION

The foregoing sections have been abbreviated as much as seemed consistent with clearness, to bring the scheme rapidly under view. Some important details need further statement, but even these must be too much abbreviated to be quite adequate.

Difference between world-ways and national thoroughfares.—An important distinction between the omninational thoroughfares on the one hand and all private, national, or even international thoroughfares on the other, whether railways or otherwise, lies in

the fact that the former are *a part of the world domain*, are in effect an extension of the high seas, while the latter are integral parts of the several national domains. This is a vital matter when the collecting of customs is considered. The bordering lines of the world-ways on land would be precisely like the borders of the sea, so far as customs regulations are concerned. Under the omninational scheme the several nations retain the same rights and privileges respecting tariffs and like fiscal systems that they now enjoy, and so the border lines of the land lanes alongside nations that impose tariffs would need to be supplied with custom-houses such as are maintained on sea borders. The normal effect would be to limit the number of stations on the omninational railways to those whose international traffic would support custom-houses. This would tend to throw the subdistribution of imported goods on the infranational lines. It is a fair presumption, however, that the increase of imports due to the facilities offered by the world-ways would more than compensate for the expense of maintenance of frequent custom-houses and that the system would be a source of tariff revenue, where tariffs are maintained, in addition to its other benefits. The bonding system would of course be applicable here as in the present system.

The terminal ports of the world-way system.—The terminal ports would obviously tend to become cosmopolitan; due recognition of this in practical provisions would be required. These provisions might go so far as to make these terminal ports free cities, with governments and fiscal systems of their own under the protection of the Confederation, or they might take the form of concessions similar to those in vogue in China, but probably in most cases less specific regulations would amply accommodate the requirements of the various peoples that assembled at the terminal ports in the natural course of business. The whole tendency of the scheme would be toward general cosmopolitanism, involving the removal of those provincialisms that make it difficult for diverse peoples to live peacefully together. Ultimately the need of any special provision for any particular people would disappear.

Some of the leading features of the omninational thoroughfares proposed in the disturbed area.—The general principle of world-ways

on land applies to the whole world, but only the war-disturbed area is specifically considered here and that only briefly.

1. The most central world-way of the proposed north-south group of Middle Europe is made to start from terminals at Saloniki on the Aegean Sea and to end in terminals near Memel at the mouth of the Niemen on the Baltic Sea, as shown on the accompanying map. It follows the valleys of the Vardar and the Morava, the eastern border of the Theiss plains, crosses the Carpathians through the Ungvar Pass, and follows the eastern border of the land inhabited dominantly by the Poles to its northeastern angle, beyond which it lies on the border between the Lithuanians and East Prussians and has its terminals near Memel at the mouth of the Niemen. It is a nearly north-south line, well suited to furnish an avenue of egress and ingress for the peoples of Serbia, Bulgaria, Rumania, Hungary, Czecho-Slovakia, Ruthenia, Poland, White Russia, East Germany, and Lithuania. Just how, as a world-owned tract under control of a world-force and protected against threatening fortifications, this world-way should serve as a barrier between peoples recently in conflict may best be seen by consulting the map.

2. The easternmost of the proposed north-south world-highways starts from terminals on the Bosphorus, runs through terminals on the Black Sea—whose western shore it skirts—and, following the valley of the Dniester, joins the preceding thoroughfare near the junction of what is now Galicia, Poland, and Russia. Thence northward it unites with the preceding to form a common trunk line to the Baltic. It is designed to give an avenue of egress and ingress for the peoples of Thrace, Bulgaria, Rumania, Ukrania, Ruthenia, Poland, White Russia, East Prussia, and Lithuania. Just how it should serve as a barrier between peoples recently at strife may be seen by consulting the map.

3. The west-central line of the north-south group starts from Fiume and Trieste at the head of the Adriatic and runs northeasterly to the junction of Croatia-Slavonia, Austria, and Hungary; thence turning northerly it runs near the border between Hungary and Austria to Presburg, at the mouth of the March valley, which it follows northward across the land of the Czecho-Slovaks to Oppeln on the Oder, from which point it is made to run within the border

of the area where Polish speech prevails, to sea-terminals on the Gulf of Dantzig. This is intended to serve as bond and barrier for the Italian, Jugo-Slav, Hungarian, Austrian, Czecho-Slovak, Polish, and German peoples, giving at once outlet and inlet to and from the Adriatic on the south and the Baltic on the north. Its relations to the problem of future peace are quite as critical as either of the preceding.

4. The westernmost of the north-south highways follows the great natural trench of the Rhine. At the same time it is intimately connected with the main east-west thoroughfare in the valley of the Danube, and the two are best considered together, for they should really form a single thoroughfare. Starting from terminals on the Black Sea near the mouth of the Danube—the same terminals that serve the easternmost north-south highway—this thoroughfare follows approximately the course of the Danube to its confluence with the Drave, which is then followed to its headwaters in the Alps near Brenner Pass in the Tyrol. Awaiting the construction of a more direct connection with the Upper Rhine by tunnel, it is proposed to use for the present the route over Brenner Pass and up the valley of the Inn to the Rhine. Thence the highway follows the Rhine to sea-terminals on the waters of the North Atlantic at the Sheldt and at the Dallart and perhaps at other points. A branch may be made to diverge from this near the angle in the Upper Rhine and extend thorugh Switzerland and France to terminals at Marseilles but this is outside the area directly involved in the war-settlement. The great east-west thoroughfare through the valleys of the Danube and the Rhine should provide at once a bond and a barrier between the peoples of Southern Russia, Rumania, Bulgaria, Serbia, Hungary, Croatia, Slavonia, Italy, Austria, Switzerland, Germany, France, Belgium, and Holland. This crosses the two central north-south highways as shown on the map and gives them east-west connections.

5. A more southerly east-west highway is proposed to pierce the heart of the Albanian-Macedonian wilds and introduce a peacemaker between the peoples of Albania, Montenegro, Serbia, and Greece, and at the same time unite the Saloniki and Bosphorus terminals. Starting from the mouth of the Drin on the Adriatic,

it follows the course of the Drin eastward and then southward past Lake Ochida to the junction of Albania, Serbia, and Greece, thence easterly near the borders of Serbia and Greece to Saloniki, and thence onward near the Aegean coast to the Bosphorus, where it connects with the easternmost of the north-south thoroughfares.

6. A short east-west connecting highway may be located on the border between Slovakia, Hungary, Ruthenia, and Rumania. Starting from the main central north-south thoroughfare at Presburg on the Danube, it may be made to run thence easterly near the southern border of Slovakia to the Saloniki-Memel thoroughfare, and thence onward across the Carpathians as near as may be along the border of the lands peopled dominantly by Ruthenians on the one side and Rumanians on the other, to a junction with the Dniester thoroughfare. Should Southern Germany form a separate nation, this line might be extended from Presburg northwesterly within the border of Bohemia and thence westerly to the Rhine. Should Russia spontaneously divide into independent or semi-independent states, this and the more northerly east-west line might be extended eastward on the same basis as the rest of the scheme.

7. Still another connecting east-west line may be located on the border between East Prussia and Poland, and thus connect the two main north-south highways near their Baltic terminals.

It will be seen that this scheme provides every nationality of moment in Central Europe with alternative ways of egress and ingress. The boundaries thus designated fairly represent the limits of the lands defined by dominance of race or language or both, and these are among the recognized criteria for homogeneous national organization and administration. This delimitation also fairly corresponds to the historical longings of the peoples themselves. But the details here presented are of course merely tentative and quite likely to need modification.

Added suggestions respecting the ruling bodies of the Confederation.—As remarked in the previous section relating to the ruling bodies of the Confederation, several alternative modes of forming such bodies are as consistent with the general scheme as that here offered. The one favored is sketched because it is somewhat out of the usual

line of governmental organization, in that it conforms to the methods of approved business practice, as seems appropriate in bodies that are to have charge of the world's greatest economic interests. The delegates of the nations are made to function as the attorneys of the national shareholders, while the directorate they select is made to serve as the directive and executive body. It is presumed that the nations will be wise enough in their own interests to appoint as their representatives men of affairs of demonstrated capacity and experience. The conduct of the affairs of the Confederation should follow as little as may be the precedents of political bodies and as much as possible the precedents of business bodies of the highest order. The work to be done lends itself happily to this.

It will be recalled that the proposed basis of representation and voting in all essential matters is to be proportionate to the participation of the respective nations in international commerce in the two respects, (1) shipping, and (2) shipped commodities, and that every nation that takes any measurable part in international exchange, and duly registers and reports it, is entitled to representation in the ratio of such exchange to the total exchange of all nations, be the amount much or little, the scheme thereby resting on the solid ground of strict equity and being really omninational.

For practical reasons, however, the *personal* representation should be limited to workable numbers, and so a unit of personal representation will need to be fixed. The standard unit in transportation might naturally be a given number of ton-miles, while that in exports and imports might be a given aggregate value. A basis for correlating the two would need also to be fixed. The representatives chosen on the basis of transportation might form a Chamber of Commerce, if the term suits; those chosen on the basis of exports and imports, a Chamber of Commercial Industries. In all cases where the commerce of a particular nation falls below the adopted units one delegate should be allowed, that all such nations may be represented. It is to be noted that this merely provides a personal representation; the *voting power* would be based solely on the commercial record of the nations, and in these cases would of course be small.

It will be necessary to define with care what constitutes *international* commerce in distinction from domestic commerce. The essential point will be to keep from the record on which representation and voting is based all commerce that is specially stimulated by financial considerations which favor one nation over others, as by a differential tariff or its equivalent. *A tariff that affects all the nations of the Confederation alike is entirely consistent with the equities of the scheme*, so far as the scheme is concerned—it is not a free-tariff scheme—but a *differential* tariff that tends to direct commerce toward one nation rather than another disturbs the parity of the system. All shipping as well as all commodities so affected should be classed as domestic or preferential exchange and excluded from the record on which representation and voting power are based.

The average of a period of years is likely to be a fairer basis for determining representation and voting power than the last annual record; perhaps the average of a five-year period might be best, the group of years to be changed annually by dropping out the first of the five years when a new year is added.

Subject to the qualifications specified, it should be the privilege of each nation to elect or to appoint its delegates to the Congress in any way it may choose, and where entitled to several delegates to determine whether they shall vote as a unit or otherwise.

It is proposed that the delegates so chosen from the several nations shall constitute the Congress of Delegates, and that this shall organize into two chambers on the basis of the particular phase of international commerce they represent.

The Congress of Delegates should have power—

(1) To enact general laws for the regulation and conduct of the affairs of the Confederation.

(2) To fix the terms of office of the directors chosen by the national delegates. These terms should be sufficiently long to secure the results of experience.

(3) To choose certain general officers to be determined in the matured scheme as adopted.

The directorate might well also consist of two bodies, one appointed by the Chamber of Commerce, whose functions should relate to the shipping interests, the other appointed by the Chamber

of Commercial Industries, whose functions should relate to imports and exports. The directors of both classes should represent the interests of the respective nations by whose delegates they were chosen, and should have the voting power of those nations. The conferring of voting power by proxy should be recognized.

The functions of the directorate would be to carry into effect all the purposes of the Confederation in essentially the same way that the directors of a corporation carry out its purposes. The specific powers conferred on the directorate should have similar range and fulness.

For the judiciary of the Confederation it is suggested that there be four courts, (1) a Court of Inquiry, whose functions shall be the determination of the facts in the cases submitted in as scientific a spirit and in as thoroughgoing a way as possible, and to report its findings to the second court, (2) a Court of Decision, whose function shall be to decide on the equities and the legal aspects of the cases brought before it, on the basis of the facts submitted by the Court of Inquiry, but it should have the power to remand any case for further investigation or to institute investigation on its own behalf; (3) a Court of Appeals, with the function implied by its name; and (4) a Court of Arbitration or Conciliation, to aid in settling controversies without formal trial. This last would often consist of special courts formed by the agreement of the parties in controversy for the arbitration of given cases.

The judges in these courts should, if a practicable scheme can be found, be appointed by the Supreme Courts of the constituent nations, co-operating on the proportionate basis that runs through the whole scheme. No two judges in any of these courts should be appointed from the same nation.

A GEOLOGICAL RECONNAISSANCE IN HAITI

A CONTRIBUTION TO ANTILLEAN GEOLOGY

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CONTENTS

INTRODUCTION

The following paper is the result of observations made during several months' work in Haiti during the spring and summer of 1918 while engaged on private work. The localities visited for

economic purposes were so widely scattered that the writer was forced to cover a large part of Haiti. Observations made are, therefore, somewhat scattered but a fairly accurate geologic section from the south coast to the north range of mountains is the result. Many of the problems could be only noted and left for future work which the writer expects to undertake.

Haiti has received but scant attention from geologists. Tertiary fossils have been collected by several people, not geologists, and have been described in the literature from time to time. L G. Tippenhauer, a civil engineer of Port-au-Prince, has published a series of maps and papers on Haiti.[1] His efforts deserve great commendation, though his stratigraphy leaves much to be desired. His text is largely geographical. His geologic mapping in so far as contacts go is generally accurate but similar formations are not always so recognized. His topography is excellent and his delineation of trails and roads uncanny in its accuracy.

With such maps available, and with a large part of Haiti, north of Port-au-Prince, of open and bare country and with excellent continuous rock exposures, the region probably is more ideal for field observation than any of the other islands. The several formations are here developed in what is doubtless their greatest thickness, and a cross-section of Haiti is a fairly complete study in Antillean geology.

In the neighboring republic of Santo Domingo practically no work has been done since the early work of Gabb,[2] excepting the recent work of Maury on the Tertiary faunas of the Rio Yaqui del Norte.[3]

The writer wishes to acknowledge the free use of the Tippenhauer maps and to use this means of expressing his gratitude to the enlisted men and officers of the U.S. Marine Corps who are stationed as officers of the Gendarmerie d'Haiti in the larger villages of the

[1] "Beiträge zur Geologie Haitis," *Peterm. Mitt.*, Bd. 45, pp. 25–29, 153–55, 201–4, 1899; Bd. 47, pp. 121–27, 169–78, 193–99, 1901; Bd. 55, pp. 49–57, 1909.

[2] W. M. Gabb, "On the Topography and Geology of Santo Domingo," *Trans. Am. Phil. Soc.*, XV (1873), 49–260.

[3] C. J. Maury, "Santo Domingo Type Sections and Fossils," *Bulletins Am. Pal.*, Nos. 29, 30, 1917; and "Santo Domingan Paleontological Explorations," *Jour. Geol.*, XXVI (1918), 224–29.

country. Their hospitality and assistance makes traveling in that country a real pleasure, where otherwise it might be anything but such.

TOPOGRAPHY

The Gran Cordillera of the island, which attains its greatest development in Santo Domingo, forms in Haiti the north range, one of three well-defined, generally parallel, ranges in the latter country. The north range forms the north peninsula of Haiti and if continued west and east from Santo Domingo, forms the Cordillera of Cuba and Porto Rico, respectively. In Haiti the highest elevation attained by this range is about 1,500 meters, while in Santo Domingo it attains in Loma Tina an elevation of over 3,100 meters, the highest peak of the Antilles.

The central range, called the "Chaîne des Mateux," extends from the west coast on the south of St. Marc to the Caribbean Sea in Santo Domingo, and attains an elevation of about 1,700 meters. These two ranges, which trend generally S. 60°–70° E. are connected by the range of the Montagnes Noires, which trends S. 45° E. and attains an elevation of 1,500 meters. Between this latter and the north range is the central plain of Haiti, which drains, not to the east, but by a deep cut through the Montagnes Noires to the west.

The south range, forming the south peninsula, attains, in the Montagne de la Selle, an elevation of about 2,700 meters, the highest point in Haiti. This range trends nearly east and west.

Between the south and central ranges and extending from the Bay of Port-au-Prince to the Bay of Barahona in Santo Domingo is a depression about fifteen to twenty kilometers wide, bounded along its entire length by the precipitous faces of the ranges on either side. Much of this depression is below sea-level and contains two lakes, both below sea-level but at different elevations. The writer expects to present a paper at some future time on this rather unique locality.

With the exception of the south range the mountains of Haiti are generally bare in appearance and a large portion of the northwestern part of the country is even quite arid. Valleys are generally fertile. The central plain is generally open grass-covered

country and in its southern part, where erosion has dissected it, presents in places the appearance of "bad" lands.

STRATIGRAPHY

A. PRE-TERTIARY ROCKS

Old Complex.—The Gran Cordillera of Santo Domingo consist essentially of a series of metamorphosed shales, sandstones, and conglomerates with extensive areas, or belts, of syenite. Gabb[1] called the metamorphosed series the Sierra group. Most of these sedimentary rocks are highly schistose. The structure, where decipherable, is complicated, forming even fan folds. Structural axes are parallel with the axis of the range.

These rocks are exposed over much of the north range of Haiti and generally lie on either side of a central intrusive belt. Tippenhauer's mapping of these areas is generally correct. Smaller areas of these rocks occur in valleys cut in the range of the Montagnes Noires. The age of these rocks is unknown. Gabb[2] called them Cretaceous, and Tippenhauer, Eocene. Both are probably wrong. The limestones from which Gabb collected *Ammonites* in Santo Domingo are undoubtedly unconformable with the schistose series. P. Frasor as early as 1888 argued an Archean age for these rocks.[3] The same series appear in Cuba and there form the base for all subsequent formations. In Porto Rico, Berkey's "Older Series,"[4] which he calls Cretaceous, are without doubt the same as the Haiti–Santo Domingo rocks though less metamorphosed. Some of the limestones and tuffs described by Berkey, especially his Coamo limestone, may be Cretaceous and correspond to Gabb's Cretaceous. Berkey's cross-section shows this Coamo member in such position that there may well be an unconformity at its base. Gabb apparently found a limestone member in the schist series and near by he found a limestone containing *Ammonites* and still in the same vicinity he found great thicknesses of limestone which are without

[1] *Op. cit.*, p. 83. [2] *Op. cit.*, p. 87.

[3] *American Geologist*, XXI (1898), 250 (citing earlier statement).

[4] C. P. Berkey, "Geological Reconnaissance of Porto Rico," *New York Acad. Sci., Annals*, XXVI (1915), 1–70.

doubt Tertiary and which flank the entire south face of the north range; and in attempting to correlate these three he found it puzzling.

Cretaceous.—Tippenhauer[1] described a formation in Haiti of undoubted Cretaceous age, similar to part of the Cretaceous series of Jamaica. This locality has not been visited by the writer. It is thought highly probable that Cretaceous rocks exist in the south peninsula. Isolated areas of sandstones, shales, and limestones occur in this region, expecially between Leogane and Jacmel, where the remnants are engulfed in late Tertiary intrusives and are generally metamorphosed (see Plate V, Section B). In this same section on the north flank of the hills is exposed a considerable thickness of tuffs which correspond in character with the Cretaceous series of Jamaica.

In the Monti Cristi Range of Santo Domingo Gabb[2] found *Orbitoides.* There is probably present there an upper Cretaceous formation of sandstones and shales, possibly the equivalent of the Richmond of Jamaica, which he failed to differentiate structurally from the overlying Miocene.

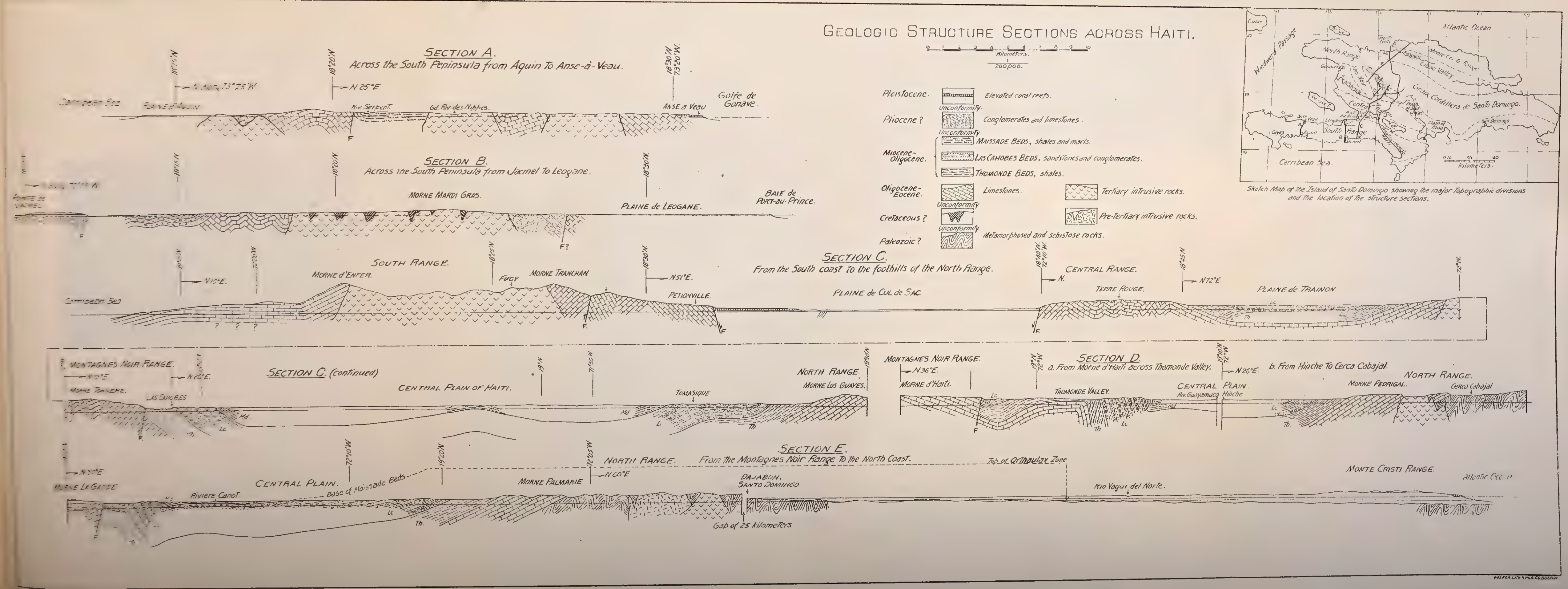
B. EARLY TERTIARY LIMESTONES

The several thick formations of limestone in Haiti have not been differentiated and there are several problems connected with them which are worthy of future work. With the exception of small areas of volcanic or intrusive rocks the entire central range, the Montagnes Noires, and a large belt along the south side of the north range are of limestone. Great thicknesses are developed and owing to continuous exposures the entire series can be carefully studied. From casual observation the series seems to consist of a basal member with considerable sandstone and above this a great thickness of very compact, light-gray or white, foraminiferal limestones, often very finely bedded but generally massive, and with intercalated beds of coralline limestone (Figs. 1 and 2).

This series rests on the older complex and the unconformity is well exposed at several places along the south side of the north

[1] L. G. Tippenhauer, *Die Insel Haiti*, Leipzig, 1893, p. 85.

[2] *Op. cit.*


Geologic Structure Sections across Haiti.
Kilometers.
1/200,000.
Section A.
Across the South Peninsula from Aquin to Anse-à-Veau.
Caribbean Sea
Plaine d'Aquin
Riv. Serbert.
Gd. Riv. des Nippes.
Anse à Veau
Golfe de Gonave
N 25°E
Section B.
Across the South Peninsula from Jacmel to Leogane.
Morne Mardi Gras.
Plaine de Leogane.
Baie de Port-au-Prince.
Section C.
From the South coast to the foothills of the North Range.
South Range.
Morne d'Enfer.
Fugy
Morne Tranchan
Petionville.
Plaine de Cul de Sac
Central Range.
Terre Rouge.
Plaine de Trainon.
Caribbean Sea
N51°E.
N72°E.
Section C. (continued)
Montagnes Noir Range.
Morne Tonnere.
Las Cahobes
Central Plain of Haiti.
Tomasique
North Range.
Morne Los Guayes.
Section D.
a. From Morne d'Haiti across Thomonde Valley.
b. From Hinche to Cerca Cabajal.
Montagnes Noir Range.
Morne d'Haiti.
N.36°E.
Thomonde Valley.
Central Plain
Riv. Guayamuco
Hinche
N26°E.
North Range.
Morne Pedrigal.
Cerca Cabajal
Section E.
From the Montagnes Noir Range to the North Coast.
Morne La Garde
Central Plain.
Riviere Canot.
Base of Maissade Beds
North Range.
Morne Palmarie
N 60°E
Dajabon, Santo Domingo
Gap of 25 kilometers
Top of Orthaulax Zone
Rio Yaqui del Norte.
Monte Cristi Range.
Atlantic Ocean
Pleistocene.
Elevated coral reefs.
Unconformity
Pliocene ?
Conglomerates and limestones.
Unconformity
Miocene-Oligocene.
Maissade Beds, shales and marls.
Las Cahobes Beds, sandstones and conglomerates.
Thomonde Beds, shales.
Oligocene-Eocene.
Limestones.
Tertiary intrusive rocks.
Unconformity
Cretaceous ?
Pre-Tertiary intrusive rocks.
Unconformity
Paleozoic ?
Metamorphosed and schistose rocks.
Atlantic Ocean
Windward Passage
North Range
Monte Cristi Range
Cibao Valley
Gran Cordillera de Santo Domingo
Central Range
South Range
Carribean Sea
Kilometers.
Sketch Map of the Island of Santo Domingo showing the major topographic divisions and the location of the structure sections.
Walker Lith. & Pub. Co. Boston

range, especially near Cerca Carbajal. All along this range the prevailing dip is to the south.

Tippenhauer[1] in a section north of Gonaïves determined a thickness of 16,500 feet for this limestone series. There is probably duplication at this place. A section the writer measured between Hinche and Cerca Carbajal showed a thickness of 13,000 feet but later the conclusion was reached that there was good evidence here of duplication. There is, however, at least in this section, a

FIG. 1.—Fine-bedded, compact, foraminiferal limestone in quarry near Gonnaïves

thickness of about 6,000 feet exposed. Southeast of Port-au-Prince, on the road to Fucy there is, however, an unduplicated section of limestone whose thickness is at least 8,000 feet (see Plate V, Section C, south range).

This same limestone on the south side of the Gran Cordillera in Santo Domingo was called Cretaceous by Gabb,[2] being included by him with other limestone of undoubted Cretaceous age. Tippenhauer has called it Miocene and Pliocene and his mapping has been done largely on the basis of the color of the rock. The conclusion that it is Eocene and lower Oligocene, prior to any paleontological work, is based on its striking similarity to the Jamaica and Cuban occurrences and also because of its position relative to overlying

[1] *Peterm. Mitt.*, Bd. 45 (1899), pp. 153–55. [2] *Op. cit.*

sediments of known age in Haiti. The Oceanic series of Hill,[1] about 2,000 feet thick, corresponds in character to the Haitian series. Cuban occurrences are also similar.

Maury[2] has described the upper Oligocene-Miocene series in the Yaqui Valley of Santo Domingo and these same formations reach a great development in Haiti, where they overlie the limestone. In a section by Tippenhauer[3] he found none of this limestone on

FIG. 2.—Foraminiferal limestone on Grand Rivière de Jacmel, south peninsula

the north side of the north range and likewise in Santo Domingo neither Gabb nor Maury mention this limestone north of the range. It is apparently entirely lacking on that side of the island. Hill[4] places a gap in middle Oligocene time between his Oceanic series and the Bowden of Jamaica, the latter of which corresponds to at least part of the Miocene of Maury's section in Santo Domingo There is, however, no structural evidence of unconformity above the limestone in Haiti. Dips are generally concordant and where they are not there is evidence of faulting.

C. TERTIARY CLASTIC SEDIMENTS

General.—Overlying the Eocene-Early Oligocene limestones is a thick series of shales, marls, conglomerates, and sandstones. This

[1] *Bull. Mus. Comp. Zoöl.*, Harvard Coll., XXXIV, 1899.

[2] *Op. cit.* [3] *Op. cit.* [4] *Op. cit.*

series underlies the entire central plain of Haiti and another area south of Mirebalais and probably underlies much of the lower valley of the Artibonite River. The beds are well exposed and are folded, highly in places, especially along the west side of the central plain, so that good sections can be seen. The whole series is very thick, perhaps as much as 10,000 feet, and is, in places, extremely fossiliferous. Some small amount of detailed work was done on these rocks and some fossils collected, though the work as yet is

FIG. 3.—Las Cahobes beds near Las Cahobes

by no means systematic. The writer expects to present further notes on this series in the near future.

Referring to the central plain area, these beds occupy a broad syncline. All along the foothills of the north range, on the east side of the plain, the beds dip southwest at varying degrees up to 35°, and as far as noted the dips are concordant with the dip of the underlying limestone. On the west side of the plain the structure is complicated by sharp flexures and in many places the contact with the underlying limestone is one of faulting.

South of Hinche in the vicinity of Thomonde an asymmetric anticline strikes off the Montagnes Noires Range in a southeasterly direction and from this vicinity on to the southeast the structure underlying the plain is that of two broad synclines with the

Thomonde anticline, which becomes broad and symmetrical, in the middle and forms the dominant feature of the structure. Along the north flank of the central range the contact between this series and the underlying limestone is probably a fault.

The northern part of this plain is very flat and grass-covered. Going south there is a progressive increase in the erosional dissections and excellent sections are exposed in the several large streams north and west of Maissade. East of Hinche along the River Samana, on the road from Hinche to Las Cahobes, and in the southerly portion of the plain in general well-exposed sections are numerous.

FIG. 4.—Las Cahobes beds rising above level of the plain, east of Las Cahobes

Limestone fragments have not been noted as entering into the make-up of the beds. The material is derived almost entirely from the old Paleozoic series and the igneous rocks associated with it.

Divisions.—In Haiti for the purpose of facilitating structural delineation the writer divided this series of sediments into three divisions, purely on a lithologic basis. The distinction holds wherever the series is exposed.

1. *Lower—Thomonde Beds*

The lowest division, called the Thomonde beds, consists almost entirely of fine-grained sediments, chiefly fine, bluish, soft shales. The thickness of this member varies and it seems to be thinner along the eastern side of the central plain. Its maximum thickness

may be 1,500 feet. It is fossiliferous to some extent but no collections were made from it.

2. *Middle—Las Cahobes Beds*

The middle division, called the Las Cahobes beds, is quite different. It consists of coarser and more consolidated rocks. In

FIG. 5.—Maissade beds on Rio Blanco near Maissade. Protruding bed is composed of *Scapharcas*.

general this member may be described as an alternating series of conglomerates, which are quite hard, with pebbles usually smaller than a robin's egg; sandy shales; some beds of coarse, unconsolidated sands; thin beds of very hard sandstone which characteristically weather out to flat rounded knobs; some limy beds, and at

some places coral limestones (Figs. 3 and 4). Also characteristic of this division are several beds composed mostly of a very thick large species of *Ostrea*. In other beds are myriads of *Scapharcas*. This division is quite fossiliferous, the conglomerate members and many of the sandstone beds, however, being generally devoid of fossils. No complete collections were made but the following species have been recognized:

LAS CAHOBES FOSSILS

LOCALITY: HILL SOUTH OF THOMONDE

Conus sp.
Cornus stenostomus Sowerby
Drilla riogurabonis Maury
Fasciolaria kempi Maury
Phos gabbi Dall
Meta perplexabilis (?) Maury
Murex domingensis Sowerby
Aspella scateroides Blainville
Strombus maoensis Maury
Turritella planigyrata Guppy
Turritella tornata Guppy
Solarium quadriseriatum Sowerby
Polinices stanislas-meenieri Maury
Sinum nolani Maury
Scapharca chiriquiensis Gabb[1]
Scapharca quayubinica Maury
Scapharca cercadica Maury
Ostrea gilbertharrisi var.[2]
Venericardia scabriocstata Guppy
Echinochama antiquata Dall
Ostrea megodon Hanley
Pecten engrammatus (?) Dall
Pecten hatoviejonis Maury
Pecten soror Gabb
Phacoides (*Mitha*) *smithwoodwardi* (?) Maury
Cardium (*Trachycardium*) *dominicanum* Dall
Tellina (*Scissula*) *cercadica* (?) Maury
Tellina cibaoica Maury
Mytilopsis domingensis Reeluz
Siliqua subaequalis Gann

[1] Occurs in massive beds.

[2] Occurs in massive beds, very much more elongated than Maury's species.

This middle division (Las Cahobes) is very thick. On the road from Hinche to Thomonde these beds are tilted to angles of from 75°–85° and the total thickness exposed is probably over 6,500 feet.

Excellent exposures of this divisions occur at many place and there are some especially interesting localities near Las Cahobes.

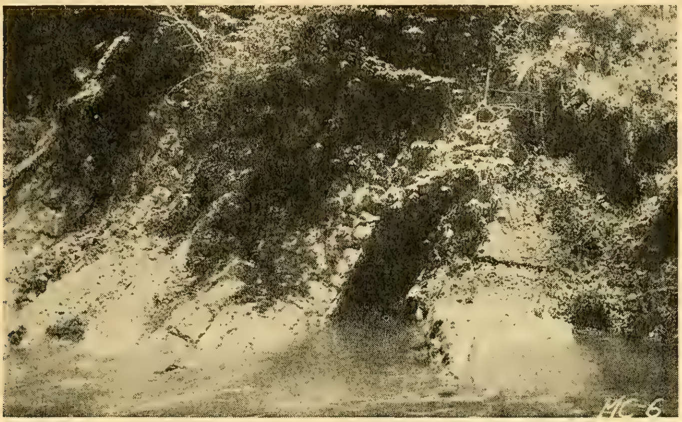


FIG. 6.—Maissade beds on Rio Blanco, showing bed of lignite

3. *Upper—Maissade Beds*

The uppermost division of this series consists of shales, marls, and some sandstones and is characterized by lignitic beds which near the town of Maissade are well defined. The division is well exposed north and west of Maissade along the Rivière Canot and its several branches, notably the Rivière Fond-de-Gras, Rio Piedre, and Rio Blanco. An excellent section is obtainable on the Rio Blanco of that part of the division containing the lignite beds (Figs. 5 and 6). Following is a detail of this locality and a list of the fossils hastily collected from it:

DETAIL SECTION ON RIO BLANCO

	FEET
Lignite, brown, flaky	6.5
Marl, gray, argillaceous	6.5
Sandstone, hard, gray	0.6
Sandstone, shaly, with masses of *Arcas* in lower part and *Ostreas* in upper part	3.5

	FEET
Clay, blue	0.6
Lignite, shaly and flaky	0.7
Sandstone, gray, lignitic streaks	5.0
Shale, with flaky lignite	3.5
Shale, gray, sandy	0.3
Clay, gray, lignitic streaks, very fossiliferous	4.5
Shale	3.3
Sandstone, fossiliferous	0.3
Lignite, shaly and flaky	1.2
Lignite	0.8
Sandstone, shaly, hard, fossils near top	0.8
Shale, black, carbonaceous	1.8
Clay, sandy, gray, fossiliferous	0.6
Clay, blue, very fossiliferous	10.5
Clay, blue, *Ostrea* bed	3.3
Clay, blue, small fossils, *Turritella*, *Ostrea* absent	4.5
Clay, blue, *Ostrea* bed with *Arcas* and other shell fragments	6.0
Clay, blue, *Turritella* bed	7.2

MAISSADE FOSSILS

Locality: Rio Blanco north of Maissade

Phos gabbii Dall
Melongena consors
Phos costatus Gabb
Potamides Roumaini Pillsbury[1]
Potamides caobensis Pillsbury[1]
Turritella planigyrata Guppy
Turritella tornata Guppy
Niso grandis Gabb
Scapharca chiriquiensis Gabb[2]
Scapharca cor-cupidonis Maury
Ostrea virginica Gmelin
Lucina chrysostoma Philippi
Mytilopsis domingensis Recluz

This division is particularly rich in fossils. The writer visited a locality on the Rivière L'Ayaye about twelve kilometers northwest of Las Cahobes to examine a lignite deposit. The lignite

[1] Very abundant, not noted in Maury's Santo Domingo section.

[2] Massive bed, see Fig. 5.

proved to be merely lignite fragments imbedded in sand. The exposure is a bluff on the east of the river and consists largely of shale beds dipping east at low angles. Pieces of the shale lay about the base of the bluff and from these pieces the following species were collected:

FOSSILS FROM MAISSADE BEDS ON RIVIERE L'AYAYE

Bullaria paupercula Sowerby
Terebra berlinerae Maury
Conus ritteredgei Maury
Conus symmetricus Sowerby
Conus sp.
Turris albida barretti Guppy
Turris albida virgo Lam.
Drillia fusiformis Gabb
Drillia consors Sowerby
Drillia henekeni Sowerby
Glyphostoma dentifera Gabb
Glyphostoma golfoyaquensis Maury
Oliva cylindrica Sowerby
Olivella muticoides Gabb
Marginella maoensis Maury
Marginella (*Persicula*) *cercadensis* Maury
Fusus henekeni var (?)
Mitra henekeni Sowerby
Latirus fusiformis Gabb
Vasum hiatense Sowerby
Melongena consors Sowerby
Phos costatus Gabb
Phos fasciolatus Dall
Metula cancellata Gabb
Strombina prisma P. & J.
Murex messorius Sowerby
Murex domingensis Sowerby
Murex (*Chicoreus*) *cornerectus* Guppy
Typhis cercadicus Maury
Cassis sulcifera Sowerby
Malea camura Guppy
Cypraea spurcoides Gabb
Strombus proximus
Strombina divilitus H. & M. (?)
Cerithium russelli Maury
Siliquaria gurabensis Maury

Turritella planigyrata Guppy
Natica (stigmaulas) sulcata Born
Amauropsis guppyi gurabensis Maury
Neretina (Smaragdia) viridemaris Maury
Neretina sp.
Astralium karlschmidti Maury
Callisotoma grabaui Maury
Melanella (Eulima) cercadica Maury
Dentallium dissimile Guppy
Potamides caobensis Pillsbury
Scapharca guayubinica Maury
Scapharca henekeni Maury
Scapharca (Cunearca) willardausteni Maury
Scapharca losguemadica Maury
Scapharca hispaniolana Maury
Pecten cereadica Maury
Lucina chrysostoma Philippi
Phacoides (Miltha) smithwoodwardii Maury
Cardium (Trachycardium) tintinabularum
Tellina islahispaniolae Maury
Mytilopsis domingensis Recluz
Corbula (Cuneocorbula) dominicensis Gabb
Corbula (Cuneocorbula) caimitica Maury
Euspamia sp.
Madrapore sp.

The Las Cahobes member of this series has resisted erosion to a greater extent than the members above or below it. Hence there is a generally well-defined valley or depression skirting the edge of the plain in its lower part which is underlain by beds of the lower or Thomonde division. The Las Cahobes beds stand above the general level of this plain and, where tilted, form hills parallel to its border (Fig. 7). Along the eastern and southern sides of the plain these hills are prominent and where the beds are nearly vertical sharp ridges are formed by the harder members, chiefly the conglomerates. Pine trees grow in the central plain but are confined to the areas of Las Cahobes rocks.

The foregoing notes will explain why the division of the series was made. It may not stand from a paleontologic viewpoint. It will prove useful, however, in future work and makes delineation of structure fairly simple.

Age and correlation.—On the general correlation table these sediments are shown in part as Oligocene and Miocene to correspond with Maury's determinations in the Yaqui Valley of Santo Domingo. What is here called the Maissade is undoubtedly the equivalent of the *Sconsia laevigata* and the *Aphera islacolonis* formations in Maury's section[1] and the equivalent in part of Hill's Bowden in Jamaica. This places the Maissade in the Miocene and it represents probably lower and middle Miocene. This being the case,

FIG. 7.—Hills formed by upturned Las Cahobes beds near Las Cahobes

at least the upper part of the Las Cahobes beds are the equivalent of the *Orthaulax inornatus* formation of the Yaqui section, which Maury places in the Oligocene. In general lithologic characters the beds so far correspond well to the Santo Domingo section, and while the work so far done in Haiti along paleontologic lines is merely the result of a few minutes collecting here and there, nevertheless there is a striking similarity in faunas, sufficient no doubt to make the correlation definite.

According to Gabb[2] the entire thickness of the lower members including the *Orthaulax inornatus* is only 600 feet. It seems evident that the entire section is not developed in Santo Domingo and that in Haiti the larger part of the entire thickness of sediments lies

[1] *Op. cit.* [2] *Op. cit.*, p. 95.

TABLE I

Correlation Table of the Eocene, Oligocene, and Miocene Formations of the Antilles

Jamaica (Hill)	Cuba (Vaughan)	Santo Domingo (Maury)	Haiti (Jones)		
	La Cruz Marl	Upper horizon of Maury (*Sconsia laevigata*)	Maissade beds 1,000′+	Middle	Miocene
Bowden	Marl at Baracoa	Zones G, H, & I of Maury (*Aphera islacolonia*)		Lower	
	Anguilla	*Orthaulax* zone	Las Cahobes beds 6,500′	Upper	Oligocene
(Missing)	Coral reef at Guantanamo	(Missing on north side) / Probably present under Plains of Azua and San Juan	- - - - - - - - - - - - - -	Middle	
	(Missing)		Thomonde beds 1,500′	- - - - - - Lower	
Oceanic series		(Present on south side)	Limestone series		
	St. Bartholomew limestone		8,000′+	Upper	Eocene

Note.— - - - - - indicates position of divisional line doubtful.

below anything yet described in the Antilles. Below the *Aphera islacolonis* formation of Maury we are dealing with formations which are absent in Jamaica, and below the *Orthaulax inornatus* and underlying beds of Santo Domingo we are dealing with formations which have probably not been encountered elsewhere in the Antilles.

Limestones and marls of upper Oligocene age are widespread in Cuba and only two isolated and local formations occur there which may be of early Oligocene age and both of these are doubtful.[1]

Berkey[2] places his Arecibo formation of Porto Rico as extending through Oligocene and Eocene but Maury[3] believes that it will prove to be the equivalent of the Santo Domingo section. Vaughan's[4] correlation table shows the "Pepino," of Porto Rico, equivalent to the lower horizon in Santo Domingo, which is middle Oligocene. In Jamaica, then, the middle and upper Oligocene are missing. In Cuba the upper, in Porto Rico the middle, and in Santo Domingo both upper and middle, Oligocene are present. It is thought, at least from Hill's description, that the entire Oceanic series (limestones) of Jamaica is present in Haiti. If this is true then either the lower horizon in Santo Domingo does not occupy all of middle Oligocene time or the Oceanic series of Jamaica does not extend to middle Oligocene; for in Central Haiti, between the two and forming a conformable series, is a large thickness of sediments which is apparently absent elsewhere in the Antilles.

RELATIONS OF EOCENE-EARLY OLIGOCENE LIMESTONES AND OLIGOCENE-MIOCENE SEDIMENTS

The foregoing notes will indicate a stratigraphic problem of some interest. First, in Haiti there is a thick series of sediments of Oligocene-Miocene age in which the lower and major part is confined to the Oligocene, and this part has apparently not been noted or described heretofore. Secondly, this series rests apparently

[1] Bailey Willis, "Stratigraphy of North America," *U.S. Geol. Survey, Prof. Paper 71*, 1912, p. 722.

[2] *Op. cit.*, p. 29. [3] *Op. cit.*, Bull. 30, p. 41.

[4] T. W. Vaughan, "Correlation of Tertiary Geological Formations of Southeastern United States, Central America and the West Indies," *Washington Acad. Sci., Proc.*, VIII, 1918, 268–76.

conformably on a series of deep-water limestones which extend through late Eocene and into early Oligocene. Thirdly, the Santo Domingo equivalents of the upper part of the Miocene-Oligocene series in the Yaqui Valley rest directly on the Paleozoic complex and the limestone series is lacking. Fourthly, in Jamaica there is a well-defined break in middle Oligocene time between the two. These relationships would point to an unconformable relationship between the two which in the Haiti section, since dips are concordant, would be a disconformity. The fact that the upper series is so thick below the late Oligocene, together with the fact that these beds contain no material derived from the limestone, and also from the fact that the limestones do not occur on the north side of the range, would seem to indicate that no unconformity exists in the Haiti section and that this set of conditions can be explained only in one way. The thick oceanic limestones were apparently formed against a coast off which there was an abrupt drop to deep water and this coast line lay across Haiti from southeast to northwest about on the line of the north range. The limestone would then be deposited in the form of abrupt overlap to the north. Uplift, which was sufficient to bring the limestone above the sea elsewhere, left it along this shore still below sea-level so that the later sediements (Thomonde, etc.) were laid down conformably on it. Gradual depression brought about overlap of these later sediments and the Santo Domingo section was deposited.

THE TERTIARY SERIES OF THE SOUTH PENINSULA

The foregoing notes apply chiefly to that part of Haiti north of Port-au-Prince and the Cul-de-Sac depression between the central and south ranges. The writer's observations on the south peninsula have been chiefly confined to following out in a general way Tippenhauer's sections[1] and modifying in some cases his interpretations of structure.

The probability of Cretaceous formations in this region have been previously noted. The Tertiary series is in general the same as in the northern part of Haiti but there seems to be a modification which points to a closer similarity in lithologic characters to the

[1] *Op. cit.*, Bd. 45, pp. 25–29, 201–4; Bd. 47, pp. 169–78.

Jamaican occurrences. This is not, of course, surprising in view of the fact that Jamaica is but a continuation of this peninsula.

The Eocene-Early Oligocene limestones are generally more finely bedded than in the central and north ranges of Haiti. The overlying Oligocene-Miocene series is represented in part in several localities—the L'Asile Valley and north of Aux Cayes, in both of which are found lignite deposits.

Near Jacmel on the south coast is a formation of conglomerate and marls and limestones which unconformably overlie the earlier

FIG. 8.—View of central plain of Haiti with Montagnes Noires in the distance

limestones and in the case of the conglomerates are largely composed of them. These beds are well stratified, are folded, and unconformably underlie the oldest elevated coral reefs (see Plate V, Section B). These beds may possibly be the equivalents of the Pliocene series of Jamaica (Manchioneal).[1]

LATE TERTIARY AND QUATERNARY DEPOSITS

Pliocene (?) beds of the central plain.—In the southerly part of the central plain of Haiti and resting upon the eroded edges of the Oligocene-Miocene sediments is a series of gravels and sands devoid of marine fossils. These beds, in distinction to the underlying series, contain many, and often well water-worn, bowlders of limestone (Fig. 8). Chert nodules from the foraminiferal limestones are

[1] Hill, *op. cit.*, p. 86.

very plentiful and the beds contain numerous fragments of petrified wood, often whole trunks of trees. Many of the sands are well cross-bedded. There is physiographic evidence to show that the region, after uplift and folding, drained to the southeast through Santo Domingo across what are now the plains of San Juan and Azua. Before the deposition of these non-marine beds the region suffered considerable erosion, perhaps through Pliocene time, for these beds, which the writer has called the Hinche beds, fill many old erosion gullies in the underlying folded earlier series. Drainage

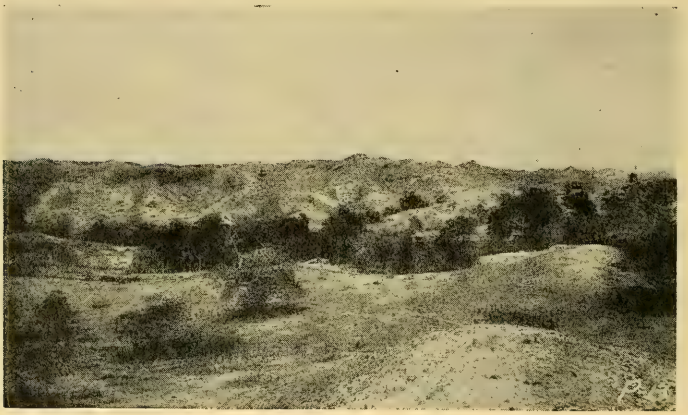


FIG. 9.—South side of central plain east of Las Cahobes. Sharp hills formed by Las Cahobes beds.

was then cut off and the region became a lake in which the Hinche beds were deposited. The floor of this lake is formed by the uppermost Hinche beds and that old floor, intact in the northern part of the plain, and largely eroded away in the southern part (Fig. 8), forms the surface of the central plain above which stand the Las Cahobes beds (see Fig. 9).

Terrace deposits.—The southern part of the central plain region is terraced (see Fig. 10) and on these terraces are loose gravels. At least four terrace levels are noted. After the deposition of the Hinche lake beds an opening was cut through the limestone range south of Las Cahobes and the plain region drained that way, the rivers following the Artibonite in its lower valley. This old cut

through the high range and through the hills of Las Cahobes beds north of that place is very distinctive.

Successive uplift and periods of quiescence brought about the terracing of this region and the dissection of the plain. Erosional remnants standing as high as the old surface are numerous. Apparently only recently has the Artibonite River passed out of the plain region through the Montagnes Noires farther west.

Elevated coral reefs and marginal deposits.—The same successive elevations and periods of quiescence which brought about the

FIG. 10.—Terraces of the central plain

terracing of the central plain region has also terraced the coast, a well-known feature of the islands of the Antilles. On many of these terraces are coral reefs and marginal sands, while coral débris is common. Near St. Marc is an elevated deposit which contains innumerable specimens of *Strombus gigas*.

IGNEOUS ROCKS

SYENITE-GRANITE

The igneous rocks of Haiti present quite a range from almost a true granite to basalt. The oldest igneous rocks are the more acid, the youngest the more basic.

The oldest rocks are the syenites and granites which occupy the large areas or belts more or less parallel with the axis of the

north range and as far as noted found only in that range. These rocks are intrusive into the old complex and their age is, therefore, indeterminate. The same rocks occur in Cuba and associated with them there are serpentines. Serpentines have not been noted in Haiti. The larger masses of these syenites and granites are fairly even-grained in texture while the smaller bodies and dikes which cut the surrounding rocks in numerous places are porphyritic. As far as known no petrographic descriptions of these rocks from Haiti have been published.

There may be still older igneous members in the Paleozoic complex but the occurrence has not been noted.

QUARTZ-DIORITE

In the region north and northwest of Gonaïves are intrusions of quartz-diorite. These intrusives cut through the foraminiferal limestone series which is generally totally recrystallized along the contacts; and locally occur contact metamorphic deposits with the usual contact minerals, garnet, calcite, chalcopyrite, magnetite, pyrite, bornite, etc.

The age of the quartz-diorite intrusion is probably late Miocene and apparently took place at the time of general uplift and folding which followed the deposition of the middle Miocene sediments.

ANDESITES

Younger and cutting through the quartz-diorites are andesites. There also occur the associated andesitic flows and breccias. While these rocks are probably associated with the same general period of igneous activity as the quartz-diorites, nevertheless the flow materials often occupy erosional depressions in the underlying rocks. Andesitic rocks occupy large areas in Haiti. The intrusive phase of the rock is somewhat variable in appearance.

BASALTS

Basalts occur at several places. There are basaltic flows from probable fissure eruptions along the northern side of the salt lakes in the Cul-de-Sac depression near Port-au-Prince.

Between the Cul-de-Sac depression and Ville Bonheur (Saut d'Eau) is a well-defined crater from which extend basalt flows. These flows occupy depressions in the present topography and have not been since modified by erosion other than the removal of fine loose material leaving along the edges of the flows loose blocks of the volcanic rock resting on underlying formations. These rocks are very recent and were poured out during one of the last eruptions in Haiti.

Deposits of volcanic ash occur at numerous places, and it is said that one or more cinder cones are located near the coast on the south side of the north peninsula.

GEOLOGIC STRUCTURE

The structure sections shown herewith are composite sections based on Tippenhauer's work and the writer's observations. The profiles are only generally correct. The sections covering the south peninsula are based on Tippenhauer's mapping with certain modifications of his interpretations. While the writer has crossed this peninsula in two places his trips were very hurried and the thick vegetation prevented him from taking more than very casual notes. From the Cul-de-Sac plain north to the foothills of the north range the section is largely the writer's, especially the part covering the central plain. The several sections across the plain are the writer's and the section across the north range is somewhat imaginary, though it does illustrate conditions in that region. The last part of the section is in Santo Domingo across the Yaqui Valley and the Monti Cristi Range and is generalized. It is inserted to show the relationships of the Oligocene-Miocene formations there to the equivalent formations of the central plain of Haiti.

The structure across the central plain region shows generally sharp flexing of the Oligocene-Miocene series along the western side of the plain, while the underlying limestones are generally faulted by thrust faults of some displacement. The sharp flexures in the later sediments are doubtless faults in the limestone beneath. A large fault is indicated well up on the south range of Haiti, a well-marked depression extending east and west along the course of this fault.

The peculiar depression between the south and central ranges is apparently a normally faulted block. The structure of this block is unknown. At only one point are the underlying rocks uncovered and here what are undoubtedly Oligocene-Miocene sediments are tilted at high angles. The indications are that this plain is a region similar to the central plain of Haiti, which was down-faulted to below sea level and has only been in part lifted above the sea in Pleistocene or Recent times. This is indicated by elevated coral reefs near Port-au-Prince.

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